https://ntrs.nasa.gov/search.jsp?R=19770017784 2020-03-22T08:50:20+00:00Z

TECH LIBRARY KAFB, NM
0061685

NASA CONTRACTOR REPORT

NASA CR-2845

LOAN COPY: RETURN TO
AFWL TECHNICAL LIBRARY
KIRTLAND AFB, N. M.

A STUDY OF THE UNIFICATION OF GROUND AND INFLIGHT WIND CRITERIA FOR THE SPACE SHUTTLE

James R. Scoggins and Gregory S. Wilson

Prepared by
TEXAS A&M UNIVERSITY
College Station, Tex. 77843
for George C. Marshall Space Flight Center

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION • WASHINGTON, D. C. • MAY 1977

TECH LIBRARY KAFB, NM

0061685

1. REPORT NO. NASA CR-2845	2. GOVERNMENT ACCESSION NO.	3. RECIPIENT'S CATALOG NO.
4. TITLE AND SUBTITLE A Study of the Unification of Ground and Inflight Wind Criteria for the Space Shuttle		5. REPORT DATE May 1977
		6. PERFORMING ORGANIZATION CODE
7. AUTHOR(S) James R. Scoggins and Gregory S. Wilson		8. PERFORMING ORGANIZATION REPORT # M-220
9. PERFORMING ORGANIZATION NAME AND ADDRESS Center for Applied Geosciences Texas A&M University College Station, Texas		10. WORK UNIT NO.
		11. CONTRACT OR GRANT NO. NAS8-29764
12. SPONSORING AGENCY NAME AND ADDRESS National Aeronautics and Space Administration Washington, D. C. 20546		13. TYPE OF REPORT & PERIOD COVERED Contractor Report
		14. SPONSORING AGENCY CODE

15. SUPPLEMENTARY NOTES
This report was prepared under the technical monitorship of the Atmospheric Sciences Division, Space Sciences Laboratory, Marshall Space Flight Center, Alabama.

16. ABSTRACT
Wind data measured on a 444-m tower located near Oklahoma City, Oklahoma, and operated by the National Severe Storms Laboratory, and Jimsphere wind profile data measured at Cape Kennedy, Florida, were used to investigate the structure of wind and turbulence in the height interval from 150 m to 1 km. Present ground wind design criteria extend from the ground to a height of 150 m, while inflight design wind criteria begin at 1 km. The primary objective of this research was to investigate the structure of wind and turbulence in the layer not encompassed by the existing design criteria and to investigate ways for unifying the ground and inflight criteria. The study encompasses steady state vertical wind profiles, directional wind component envelopes, wind shear, wind direction change, gust factor, and turbulence spectra. A method is proposed for the specification of steady state wind profiles and shear envelopes for use in the region between 150 m and 1 km without altering in any way the existing design criteria. The data analyzed did not indicate a need for changing the existing criteria in regards to wind direction change, gust factor, or spectra of turbulence.

17. KEY WORDS Wind Profile; Ground Wind Measurements; Jimsphere	18. DISTRIBUTION STATEMENT STAR Category 47

19. SECURITY CLASSIF. (of this report) UNCLASSIFIED	20. SECURITY CLASSIF. (of this page) UNCLASSIFIED	21. NO. OF PAGES 52	22. PRICE $4.50

*For sale by the National Technical Information Service, Springfield, Virginia 22161.

FOREWORD

This is the final report for NASA Contract NAS8-29764. A previous report (NASA CR-2650) titled "Structure of Atmospheric Turbulence in the Friction Layer Below 500 Meters" was concerned with the structure of atmospheric turbulence determined from tower data. This report extends some of the analysis to 1 km by use of Jimsphere data, which overlaps ground and inflight wind design criteria, and considers the unification of the criteria.

This research was conducted by Texas A&M University for the National Aeronautics and Space Administration, George C. Marshall Space Flight Center, Huntsville, Alabama. The Contract Monitors were Dr. George H. Fichtl and Mr. Dennis Camp.

AUTHORS' ACKNOWLEDGMENTS

The authors are indebted to Mr. Stephen J. Maas for the preparation of computer programs and for his assistance in data analysis, to Miss Marilyn Kocurek for keypunching the Jimsphere data, to Mrs. Nancy Fucik and Miss Doreen Westwood for preparation of the figures, to Dr. George H. Fichtl and Mr. Dennis Camp for providing data, guidance on the conduct of the research, and answering numerous calls for assistance, and to Miss Karen Cobbs for typing the final manuscript.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

A STUDY OF THE UNIFICATION OF GROUND AND INFLIGHT WIND CRITERIA FOR THE SPACE SHUTTLE

by

James R. Scoggins[1]

and

Gregory S. Wilson[2]

Center for Applied Geosciences
Texas A&M University

1. INTRODUCTION

A. Present atmospheric design criteria

The wind criteria established by NASA is divided into ground and inflight based upon engineering and operational requirements, atmospheric wind structure, and wind measurement capabilities (Daniels, 1973). The ground and inflight wind criteria model and define the wind structure based upon measurements obtained at fixed locations at the ground and from vertical wind profiles. These criteria contain wind direction and speed changes, shears, steady state profiles, gusts, and turbulence spectra.

Ground wind criteria satisfy engineering requirements for on-pad and launch winds for vertically ascending vehicles, and establish wind models for horizontally flying vehicles for take-off and landing, both of which are needed for the Space Shuttle. The ground wind data used to establish these wind criteria are obtained from a 150-m meteorological tower facility so that ground wind design criteria extend from the surface to 150 m.

Inflight design wind criteria are used primarily in vehicle design studies to establish structural and control system capabilities and to compute performance requirements. The inflight wind criteria are determined from inflight wind profiles measured by various methods and sensors which include the rawinsonde, the FPS-16 Radar/Jimsphere system, and the rocketsonde. Wind profiles are used to define the inflight wind criteria above 1 km.

The ground and inflight design wind criteria define the atmospheric wind structure in the surface boundary layer and free atmosphere,

---

[1]Professor of Meteorology and Associate Dean for Research

[2]Research Assistant

respectively. However, the criteria do not define the wind structure in the layer between 150 m and 1 km.

B. Scope and objectives of present research

The primary objective of this research is to establish a unified model which combines the surface and inflight wind criteria. The integrated model would then define the design wind criteria and wind structure in that part of the planetary boundary layer (150-1000 m) between the currently accepted ground and inflight wind criteria. In the unification of the criteria, consideration will be given to steady state and component vertical wind profiles, wind shears, gusts, wind speed and direction changes, and turbulence spectra.

The merging procedure must tie together two distinctly different wind regimes. The atmospheric boundary layer which extends to a height of several hundred meters contains a flow regime controlled by a balance of forces between the horizontal pressure gradient, the Coriolis force, and friction. In this layer all forces have approximately the same order of magnitude. The free atmosphere above the boundary layer (above approximately 1 km) contains a flow in which the horizontal pressure gradient force essentially balances the Coriolis force to produce quasi-geostrophic motion. The resulting flow patterns in both layers, particularly in the atmospheric boundary layer, produce meso- and micro-scale motions that significantly affect the vertical wind shear, gust structure, and turbulence spectrum. Recent investigations of some important aspects of these small-scale motions will be considered relative to design wind criteria.

2. DATA UTILIZED

A. Tower data

To assist in extending the currently accepted design ground wind criteria above 150 m, two sets of data collected from the 444-m meteorological tower facility of the National Severe Storms Laboratory (NSSL) located 10 km (6 mi) north of Oklahoma City were used in this investigation. The characteristics of the data sets are summarized in Table 1. Temperature values were reported to the nearest hundredth of a degree Celsius, wind speed to the nearest tenth of a m s^{-1}, wind direction to the nearest tenth of a degree, and vertical velocity to the nearest hundredth of a m s^{-1}.

Table 1. Summary of the two data sets obtained from the NSSL meteorological tower facility

DATA SET	DATE	TIMES (CST) START/STOP	OBSERVATIONS	Δt (SEC)	INSTRUMENTED LEVELS (m) SPEED & DIR.	TEMP.	VERT. MOTION
I	18 June 1971	13:35:04/ 14:34:48	1793	2	26,45,90, 177,266,355, 444	26,45,90, 177,266,355, 444	26,177,444
II	4 May 1972	12:00:00/ 15:59:50	1439	10	26,45,90, 177,266,355, 444	26,45,90, 177,266,355, 444	26,177,444

These data were provided by NSSL in the form of magnetic tapes. Although both sets are a few seconds short of an hour in length, all statistical parameters were assumed to apply to a 1-hr period.

The dominant synoptic feature on the day Data Set I was obtained (18 June 1971) consisted of a frontal system extending from the Great Lakes across the northern Great Plains to a weak cyclone in western Kansas. Although the front triggered squall-line activity throughout the day in Iowa and southern Minnesota, the front remained stationary some 600 km (400 mi) to the northwest of the NSSL tower site.

At 0600 CST (1200 GMT) skies over central Oklahoma were clear and temperatures ranged a few degrees above 70 F. Winds were from the south to southwest at around 5 m s^{-1}. By 1200 CST (1800 GMT) the temperature had climbed to above 90 F and a few towering cumuli had begun to appear. The frontal system was in the process of dissipating and winds had become steady from the southwest at around 7 m s^{-1}. A few scattered thunderstorms had developed in northeastern Arkansas. By 1500 CST (2100 GMT) the front had dissipated and the associated cyclone was filling -- winds around the NSSL site had switched direction more toward the south and southeast and had decreased in speed to between 5 and 7 m s^{-1}. Temperatures remained around 95 F and the sky had become partly cloudy with cumuli and towering cumuli having bases in the range from 1500 to 2300 m (5000 to 7500 ft) predominating. None of the radar summaries for the day showed shower activity in Oklahoma.

The major synoptic influence on the local weather conditions during the time period covered by Data Set II was provided by an extensive anticyclonic system covering the greater part of the central United States. Although the center of the system remained stationary in southern Arkansas, the pressure gradients on the back side of the anticyclone were observed to strengthen during the period. Some organized cloud regions existed to the north in Nebraska and Missouri, but no significant weather was indicated at the tower site throughout the sampling period. Temperatures were in the low 70's through the early afternoon, with southeasterly surface winds increasing from around 10 to 20 m s^{-1} through the period.

The instrumentation on the 444-m NSSL tower facility has been described in detail by Carter (1970). Measurements of horizontal wind speed and direction at all levels were made by Bendix Friez Model 120 Aerovanes. Each instrument is mounted 3.04 m (10 ft) from the tower on a boom aligned to an azimuth angle of 240 deg. The effect of the tower on measured wind speeds is considerable only for wind directions between 350 and 70 deg; the prevailing wind direction during this study was around 170 deg. The sensor has a speed threshold of 0.84 m s^{-1}, an accuracy of $\pm$ 0.25 m s^{-1}, and a distance constant of 4.66 m. Carter (1970) concludes from the instrument response criteria that estimates of gust amplitudes of higher frequency speed and direction improve with increasing mean wind speeds, so that measurements of finer-scale frequency are more accurate near the top of the tower than near the ground.

The sensitivity of turbulence measurements made by use of the Model 120 Aerovane has been described by Scoggins (1966), who compared the output of several wind sensors simultaneously exposed to the same wind conditions. The response of the Aerovane as compared to three other anemometers (generally considered "more sensitive" to turbulent fluctuations) at wind speeds comparable to those observed in the data set is shown in Table II.

Of the four instruments studied, the Aerovane recorded both the lowest mean wind speed and variance values over the sampling period; however, the portion of the total variance not measured is due almost exclusively to fluctuations with periods shorter than 5 s. The power spectra in Fig. 1 show the observed partitioning of the total variance among the various harmonics for each instrument; the solid vertical line denotes a harmonic period of 4 s on the abscissa. The portion of the figure to the left of the vertical line, which includes the range of fluctuations considered in this paper, shows that the spectral curve associated with the Aerovane approximates those obtained from the other (more sensitive) anemometers. Only to the right of the vertical line does the variance attributed to the various harmonics of the Aerovane differ markedly from the other wind instruments. Thus, for the range of frequencies under investigation in this report, the Model 120 Aerovane appears to be adequate.

B. Jimsphere data

While NSSL tower data were used to extend the ground wind criteria to 444 m, a data set containing 3755 FPS-16 Radar/Jimsphere detailed wind profiles from 100 to 2000 m, was used in conjunction with the tower data as a basis to connect ground and inflight design wind criteria. The Jimsphere data set was obtained during all types of weather conditions over a ten-year period from December 1964 to December 1974 at the Eastern Test Range and contains wind direction and speed on each profile at 20 levels from 100 m to 2000 m (some data are missing, particularly at the lower levels). The Jimsphere wind data then overlapped both the established ground wind criteria between 100 and 150 m, the NSSL tower data between 100 and 444 m, and the inflight criteria between 1000 and 2000 m. The overlapping data allowed a comparison between currently accepted and newly computed wind criteria and also aided in developing merging procedures.

TABLE II

Comparative response of various wind-measuring instruments

ANEMOMETERS	MEAN WIND SPEED (m sec^{-1})	VARIANCE ABOUT MEAN (m^2 sec^{-2})	PERCENT VARIANCE FOR P>5 sec
B&W 50	6.73	1.66	0.89
CLIMET C1-14	7.77	1.14	0.91
B&W 101	7.97	2.26	0.93
AEROVANE 120	6.16	0.99	0.99

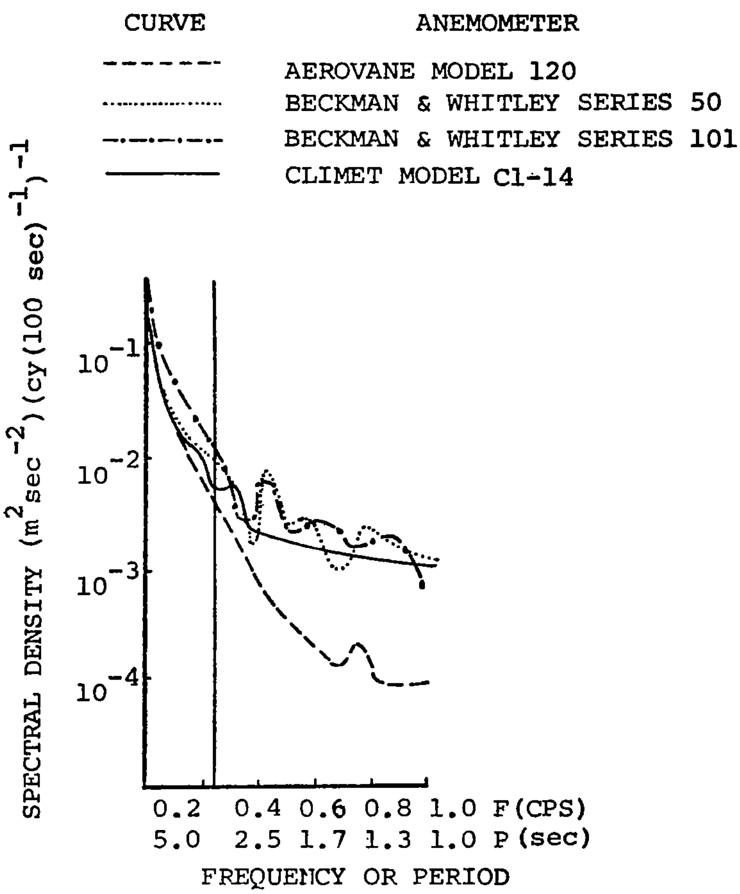


Fig. 1. Power spectra obtained from various wind-measuring instruments.

3. RESULTS OF THE DATA ANALYSIS

The analysis of both the NSSL tower data and Jimsphere data was programmed to include computation of all possible design wind criteria relative to the currently established criteria. The results that follow in this section present only the initial analysis for the tower and Jimsphere data. Comparison of these results with the currently established criteria and recommendations for changing or merging present wind criteria using these results will be presented in the next section.

A. Steady state vertical wind profiles

Cumulative percentage frequencies (CPF) for scalar wind speed (the instantaneous wind speed indicated by the Aerovane) as a function of height (26-444 m) are given in Figs. 2 and 3 for tower data Sets I and II, respectively, for various percentiles. Both data sets reveal a sharp increase in wind speed (1-2 m s^{-1}) for all percentile levels in the surface boundary layer from about 26 m to about 150 m. From the 150-m level to the 444-m level, scalar wind speeds show little change (usually <0.5 m s^{-1}) for most percentile levels in both sets of data. Maximum wind speeds are usually reached above the 400-m level in both figures with a very slight tendency for speeds to decrease (<0.2 m s^{-1}) as the top of the tower is reached, especially in data Set I.

Wind speeds were generally about 1-2 m s^{-1} lower in Fig. 2 than in Fig. 3 for all percentile levels. At the 95 percentile level, wind speeds ranged from about 7.5 to 9.0 m s^{-1} in Set I, and 9.7 to 11.2 m s^{-1} in Set II.

CPF data for the scalar wind speed (the mean wind speed as measured with the Jimsphere system averaged over approximately 100 m in the vertical direction) profiles computed from the Jimsphere data are shown in Fig. 4. Again, a sharp increase in scalar wind speed occurs in the surface boundary layer from about 100 m to 200 m for percentile levels $\geq$ 75. The percentile values from 50 through 90 show a slight decrease in speed (<1 m s^{-1}) from about 200 to 700 m, then a slight increase up to 2000 m. The percentile values greater than 90 show a slow but steady increase in wind speed between 200 and 2000 m.

At the 95% probability level, wind speeds ranged from 10.9 m s^{-1} at 100 m to 16.8 m s^{-1} at 2000 m.

B. Directional wind component envelopes

Figure 5 presents the CPF data at various percentile levels for wind components at seven levels (26, 45, 90, 177, 266, 355, and 444 m) from

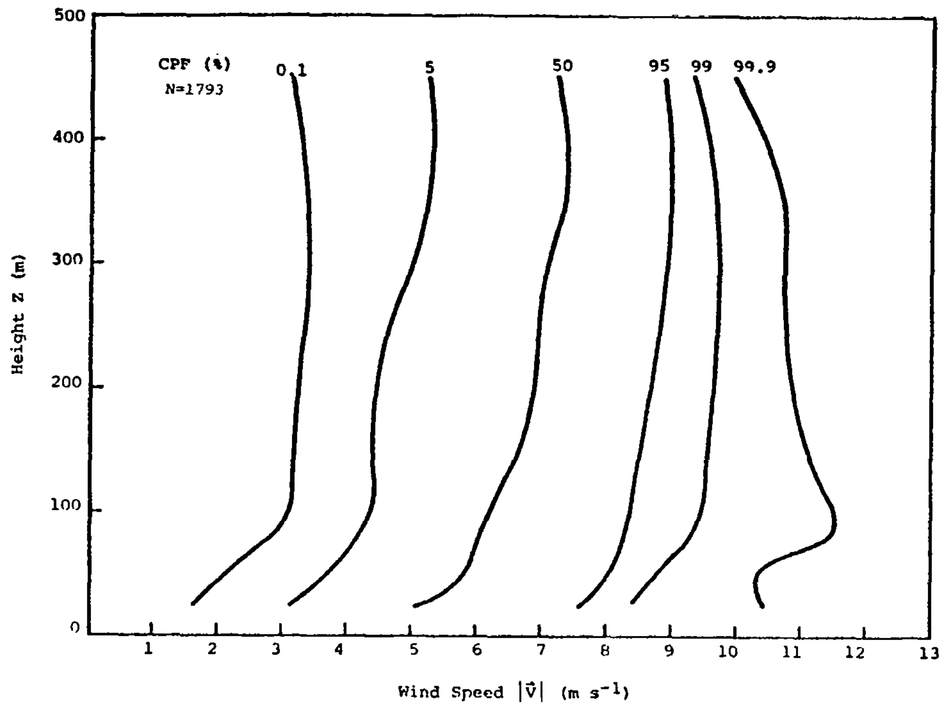


Fig. 2. Profiles of scalar wind speed for selected percentiles for tower data Set I.

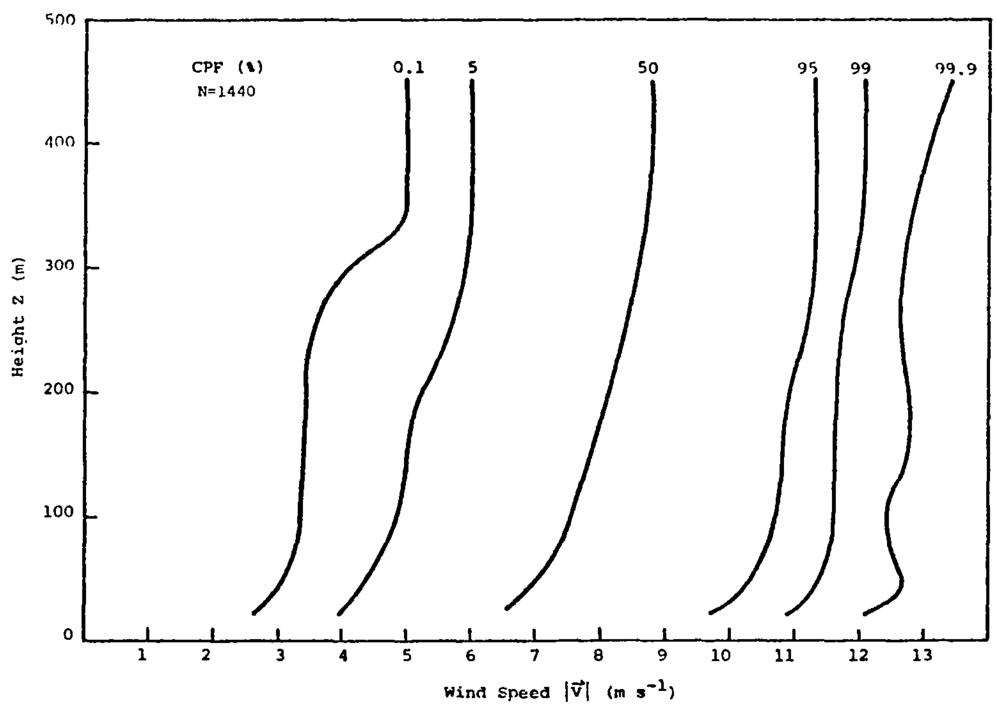


Fig. 3. Profiles of scalar wind speed for selected percentiles for tower data Set II.

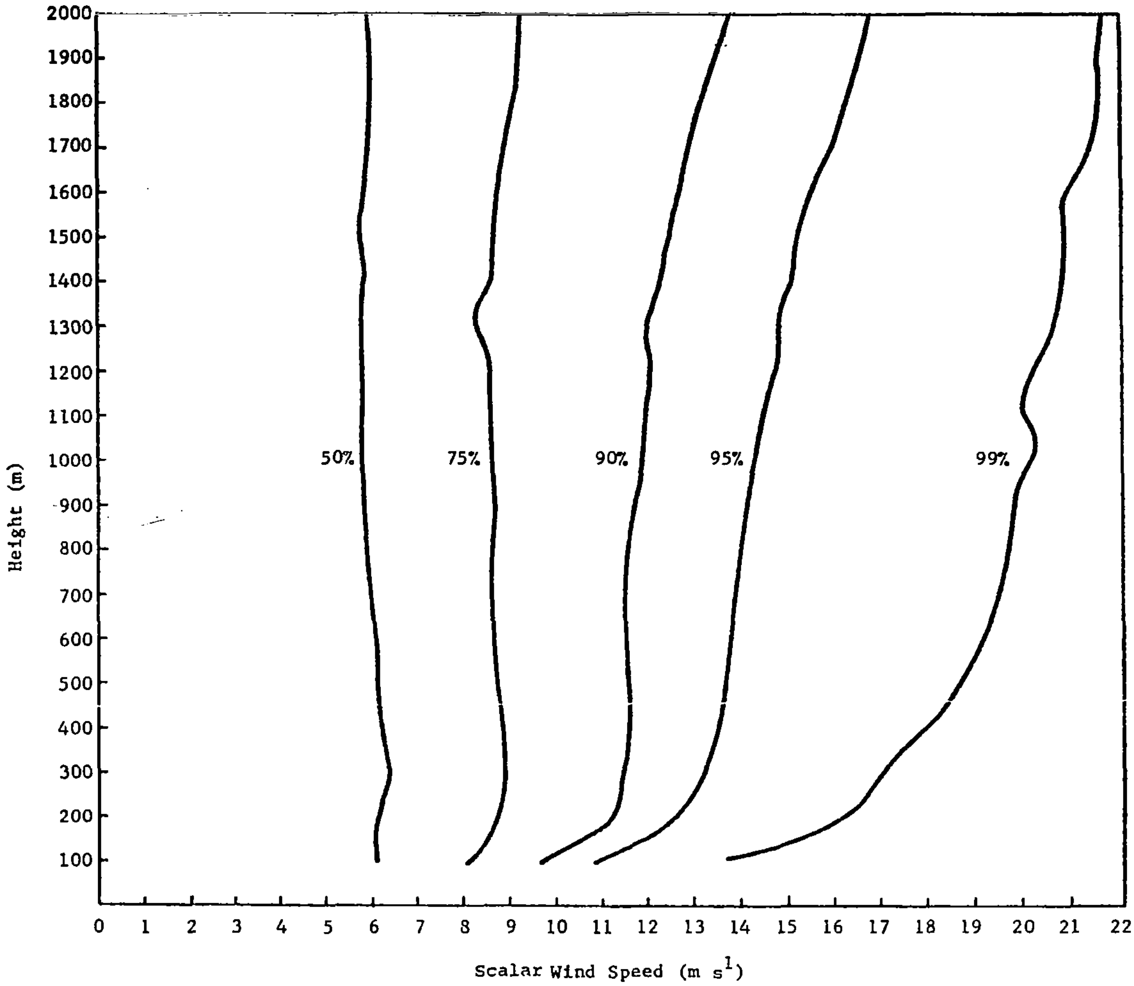
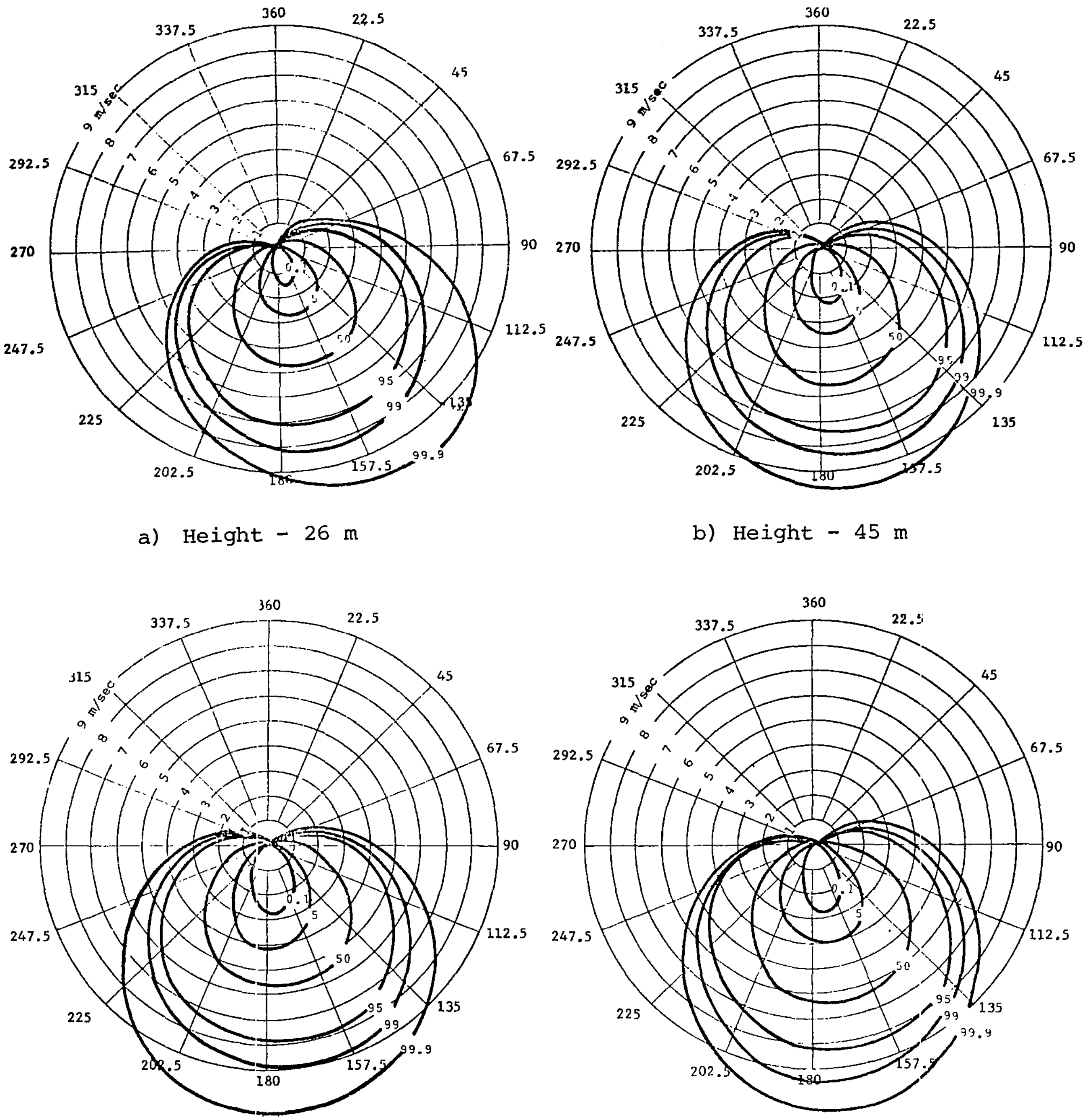


Fig. 4. Profiles of scalar wind speed for selected percentiles for Jimsphere data.



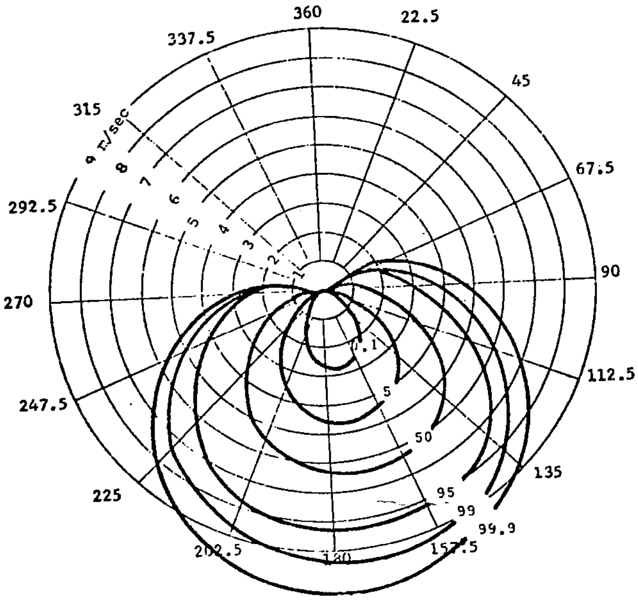
a) Height - 26 m

b) Height - 45 m

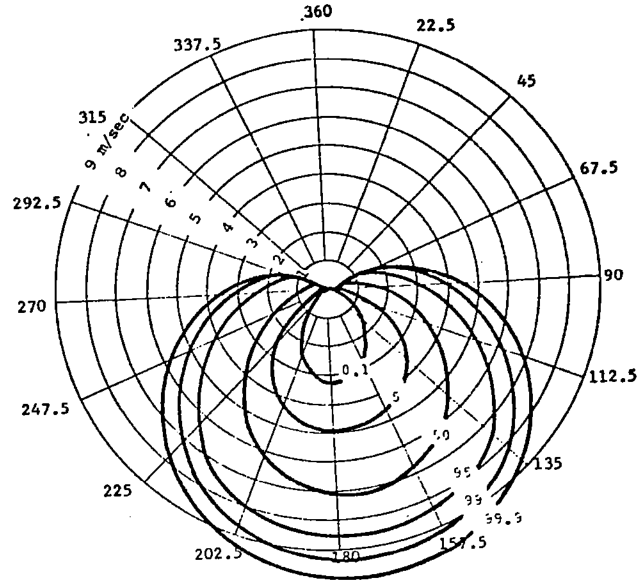
c) Height - 90 m

d) Height - 177 m

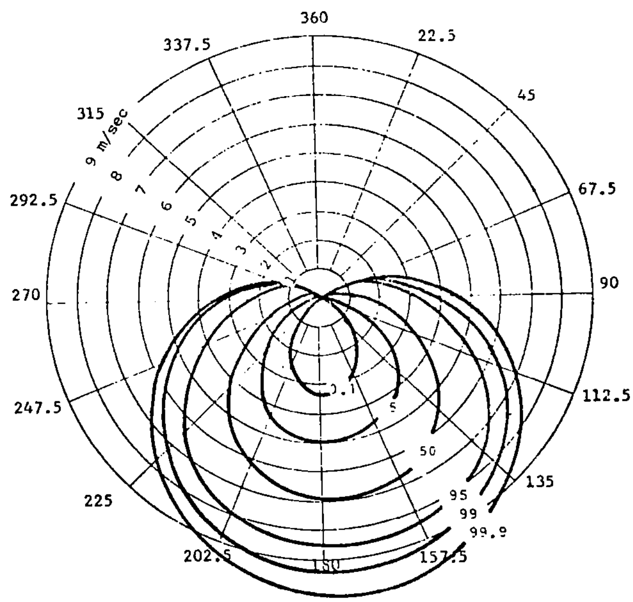
Fig. 5. Directional wind component envelopes for tower data Set I for various percentiles. (Percentiles were computed by rotating the coordinate system at 22.5° intervals through the entire 0-360° range with the plotting convention chosen to indicate the direction from which the wind was blowing).



e) Height - 266 m



f) Height - 355 m



g) Height - 444 m

Fig. 5. (Continued)

tower data Set I. Percentiles were computed by rotating the coordinate system at 22.5° intervals through the entire 0-360° range with the plotting convention chosen to indicate the direction from which the wind was blowing.

The maximum component speed at all percentile levels is oriented toward about 160° at the 26-m level and slowly veers with increasing height to a direction of 180° at the 444-m level indicating the strong dominance of a south-southeast wind.

Directional wind component envelopes for the Jimsphere data are shown in Fig. 6. Envelopes were computed at each of the 20 data levels from 100 to 2000 m using all 3755 Jimsphere profiles. The number, N, of data points is given for each level.

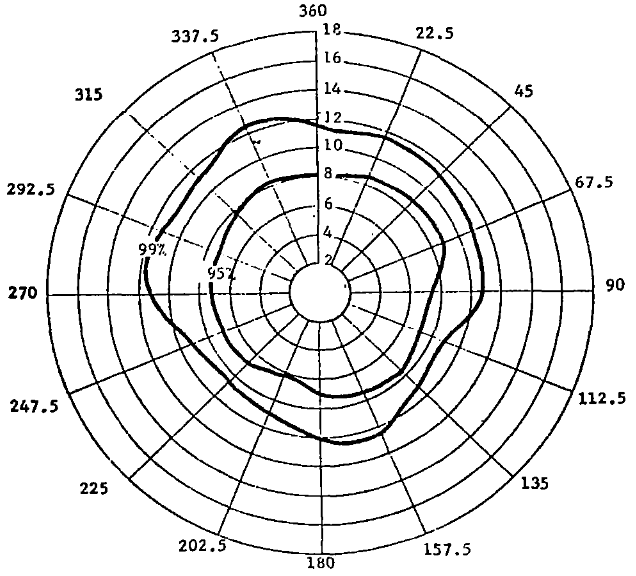
At the 100-m level, irregular shaped envelopes were computed in which component winds showed no clear dominant direction. The resulting envelopes were somewhat circular with a center close to the 0 m s^{-1} component speed so that winds at this level showed little directional dependence. However, at 200 m the maximum component wind speed axis was clearly oriented toward about 170° and this axis slowly veered with increasing height above 200 m to a final direction of about 260° at the 2000-m level.

At all levels, the computed component envelopes encompassed the entire 0-360° range so that component winds occur in all directions in the layers from 100 to 2000 m while components speeds are dominated slightly by southerly and westerly directions. For all azimuths at each altitude the 50 percentile value of wind speed was less than 2 m s^{-1}.

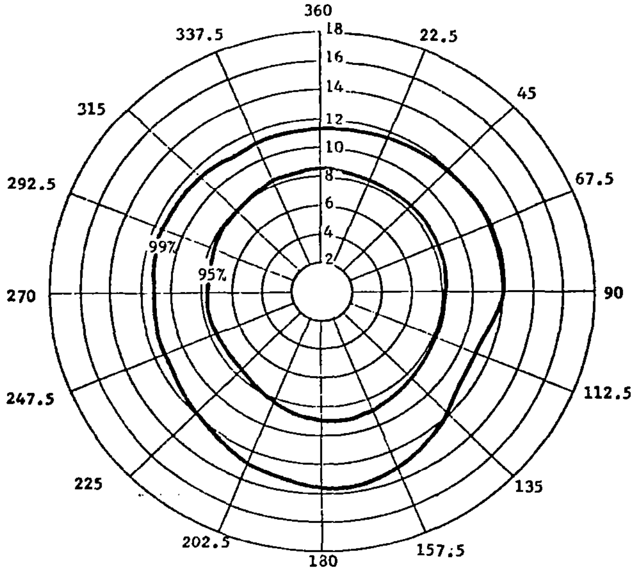
C. Wind shear

Figures 7 and 8 show CPF data for vector wind shear ($s^{-1} \times 10^{-2}$) (vector difference between wind vectors at two different heights divided by the difference in height, ΔZ) plotted against ΔZ from the 26-m level to each higher level for tower data Sets I and II, respectively. The intervals over which the shears were computed were 19, 64, 151, 240, 229, and 418 m.

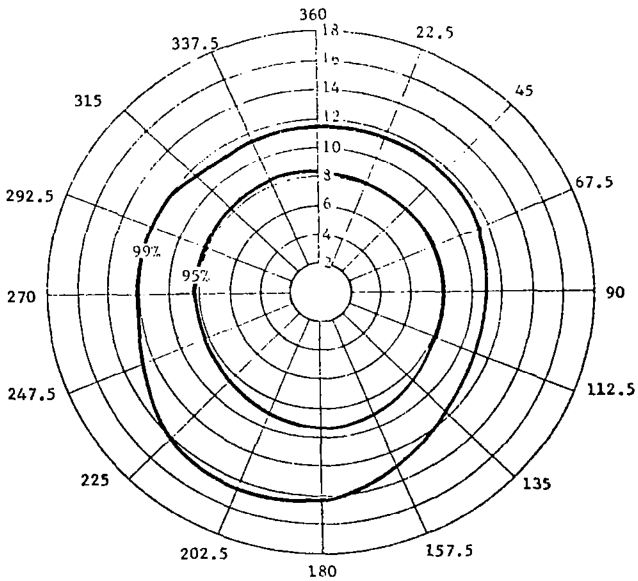
Both figures show, at all percentile levels, that vector wind shear is a function of the ΔZ over which it is computed. The shear changes rapidly with ΔZ for $\Delta Z<200$ m, then changes more slowly with ΔZ for $\Delta Z>200$ m. Only small differences exist between Figs. 7 and 8 relative to the shape and magnitudes of the vector shears. At the 99 percentile level, vector wind shear in Set I ranges from 18.8×10^{-2} s^{-1} to 1.7×10^{-2} s^{-1} while Set II shows a range from 17.3×10^{-2} s^{-1} to 1.9×10^{-2} s^{-1}.



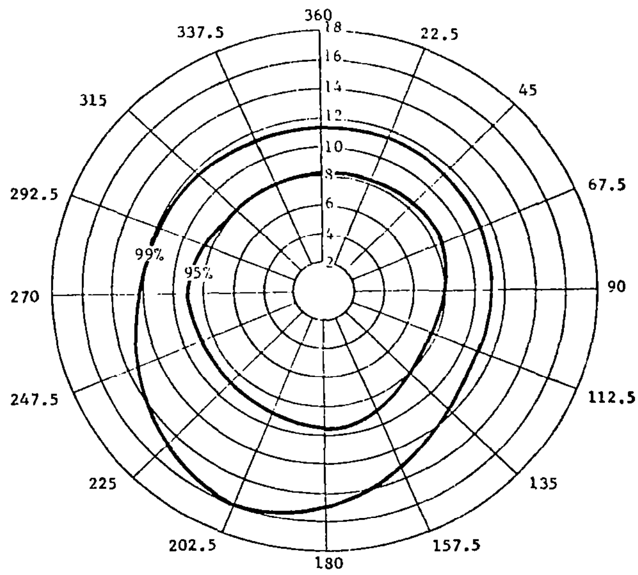
a) Height - 100 m
N = 462



b) Height - 200 m
N = 2447

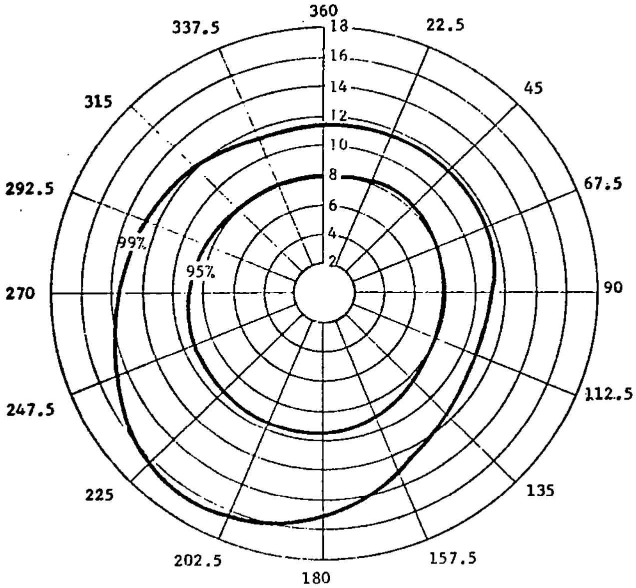


c) Height - 300 m
N = 2899

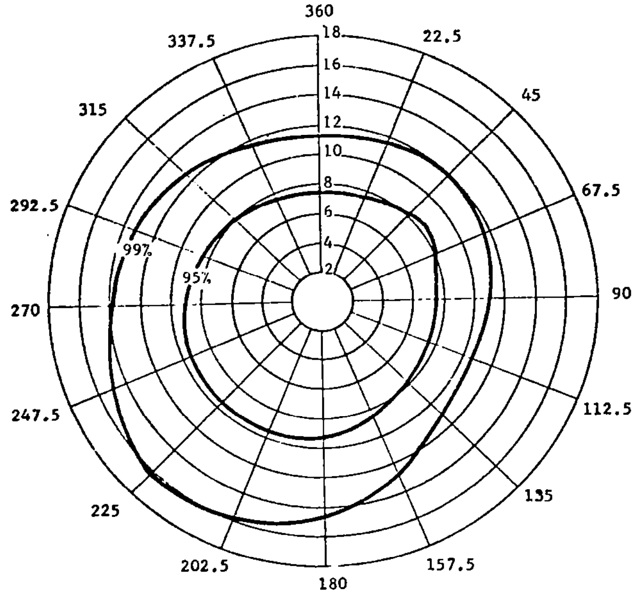


d) Height - 400 m
N = 3096

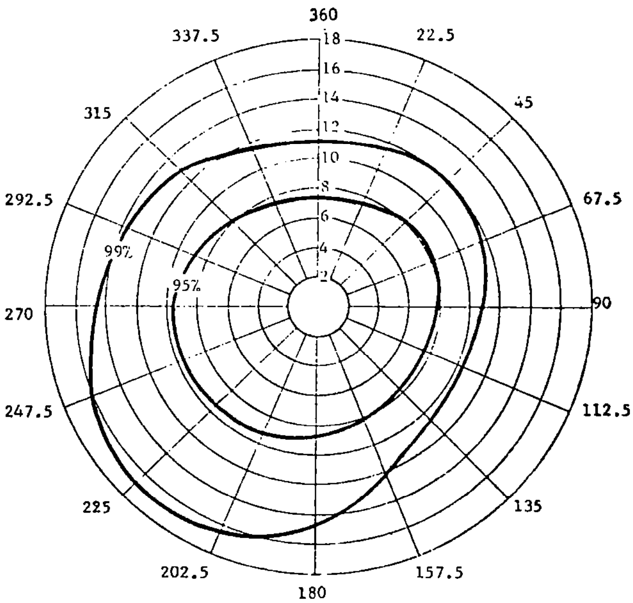
Fig. 6. Directional wind component envelopes for Jimsphere data (Cape Kennedy) for various percentiles. (Percentiles were computed by rotating the coordinate system at 22.5° intervals through the entire 0-360° range with the plotting convention chosen to indicate the direction from which the wind was blowing).



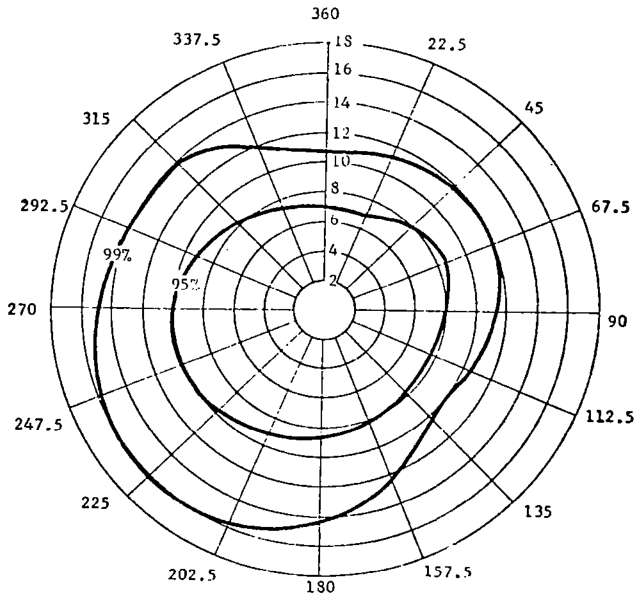
e) Height - 500 m
N = 3165



f) Height - 600 m
N = 3217

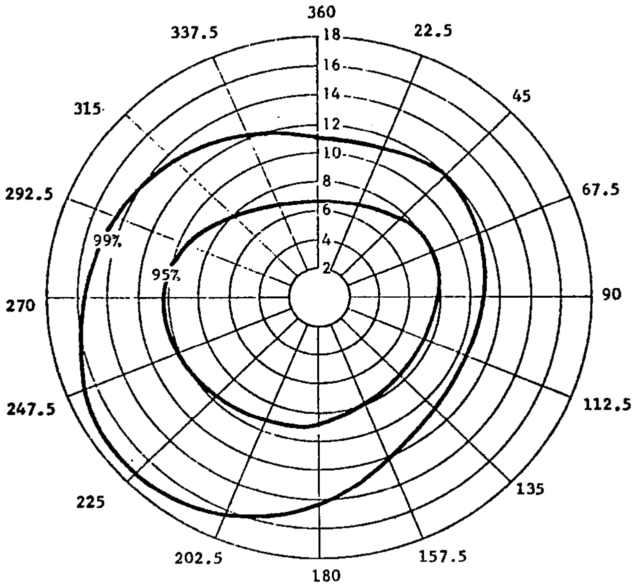


g) Height - 700 m
N = 3255

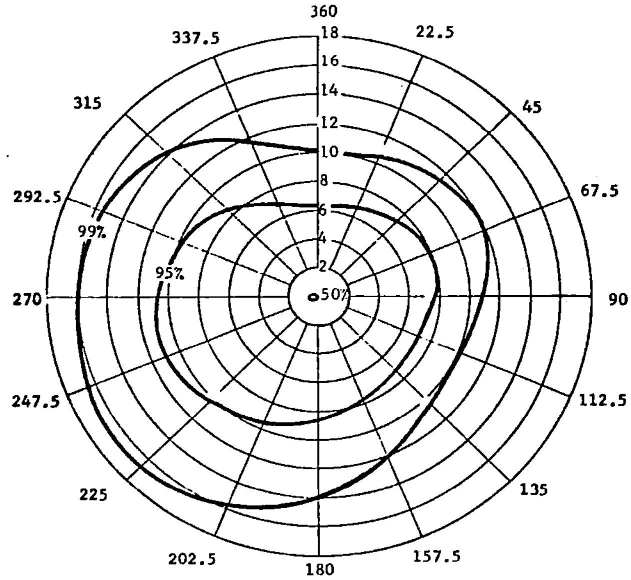


h) Height - 800 m
N = 3281

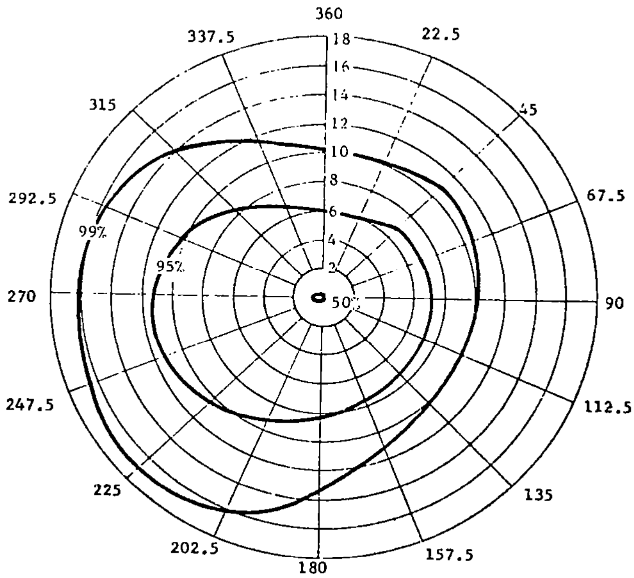
Fig. 6. (Continued)



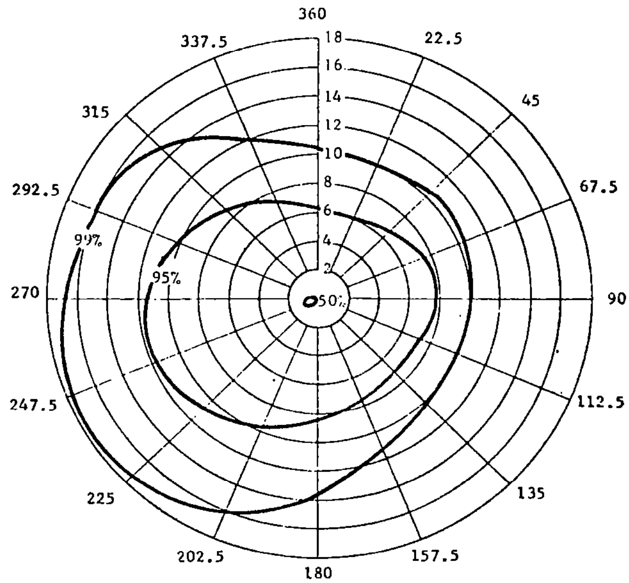
i) Height - 900 m
N = 3306



j) Height - 1000 m
N = 3329

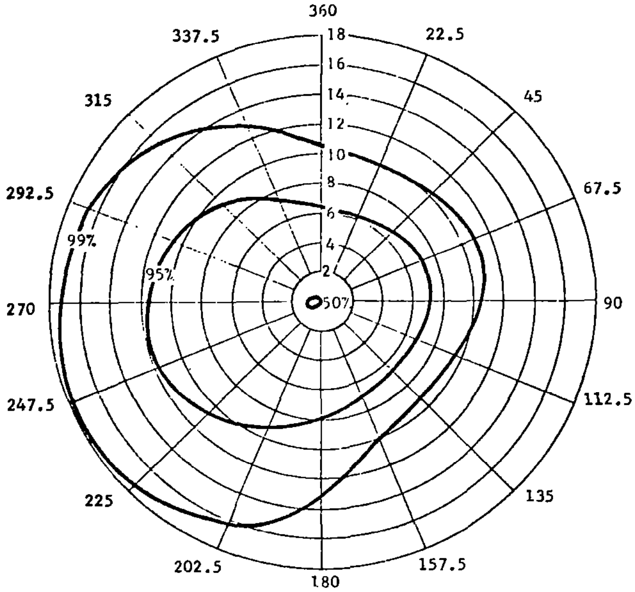


k) Height - 1100 m
N = 3354

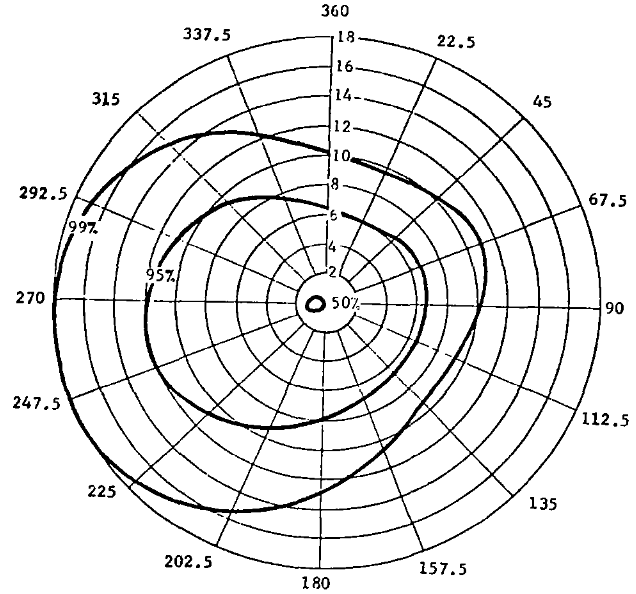


l) Height - 1200 m
N = 3370

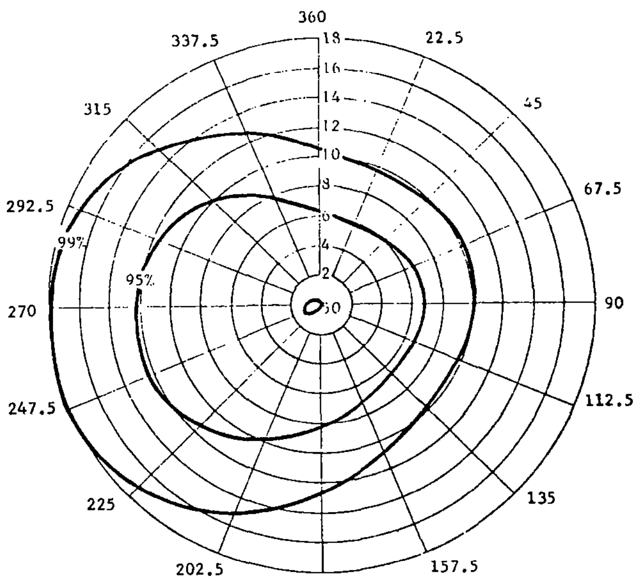
Fig. 6. (Continued)



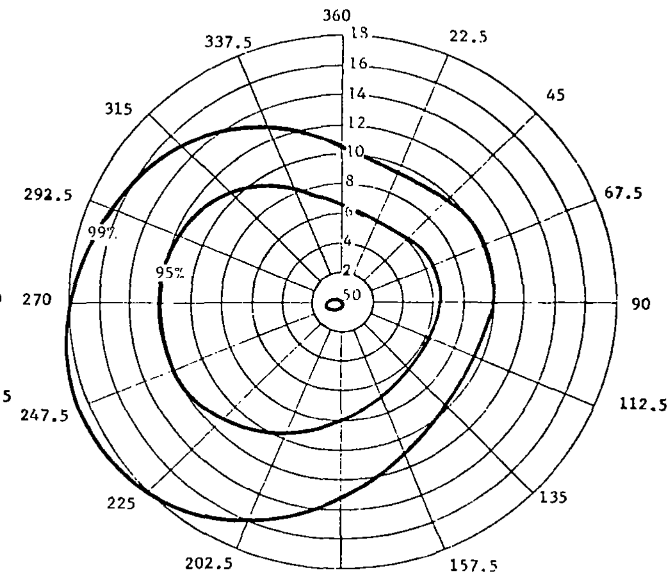
m) Height - 1300 m
N = 3392



n) Height - 1400 m
N = 3416

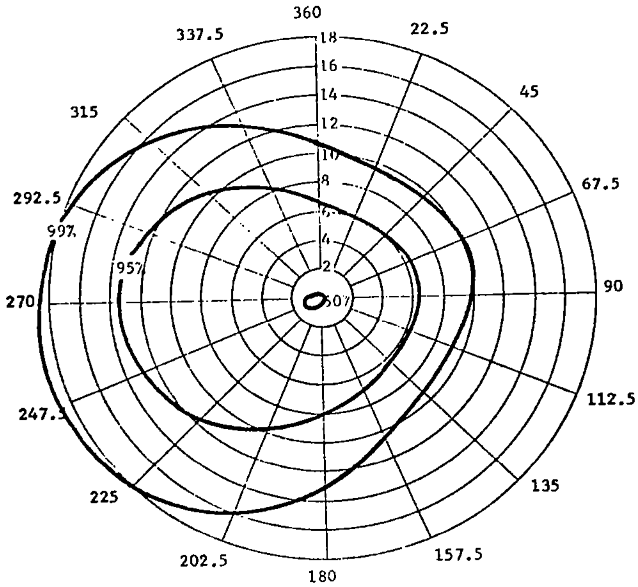


o) Height - 1500 m
N = 3341

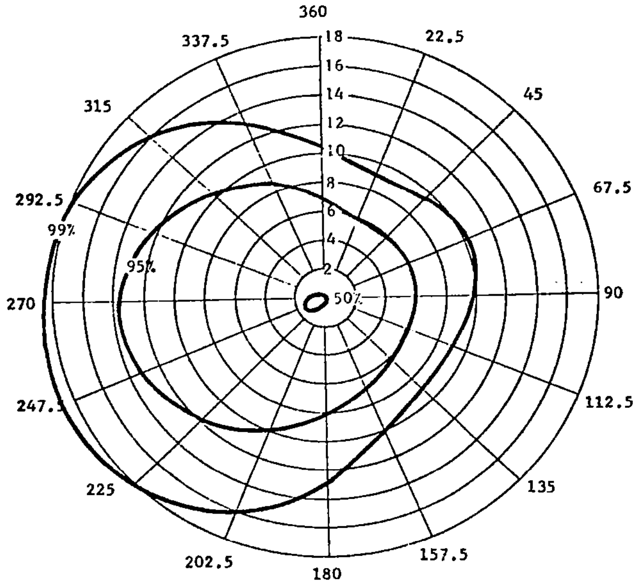


p) Height - 1600 m
N = 3449

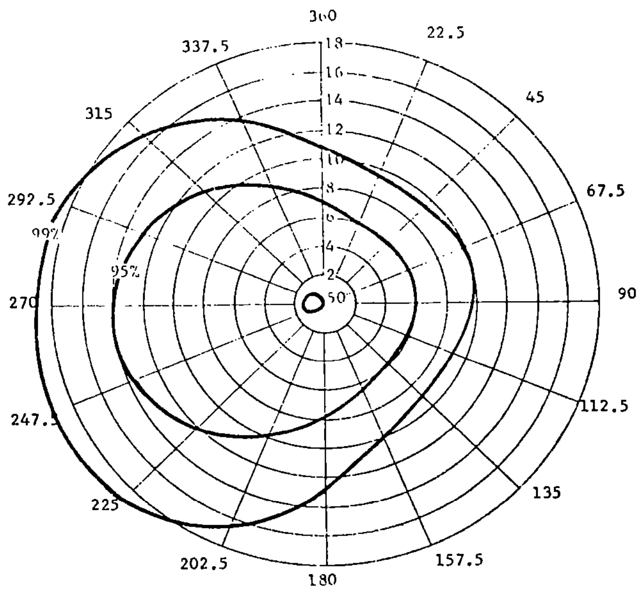
Fig. 6. (Continued)



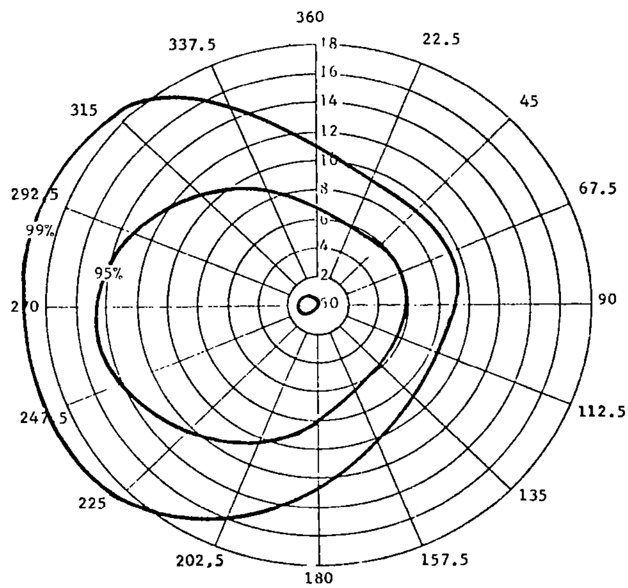
q) Height - 1700 m
N = 3471



r) Height - 1800 m
N = 3487



s) Height - 1900 m
N = 3500



t) Height - 2000 m
N = 3507

Fig. 6. (Continued)

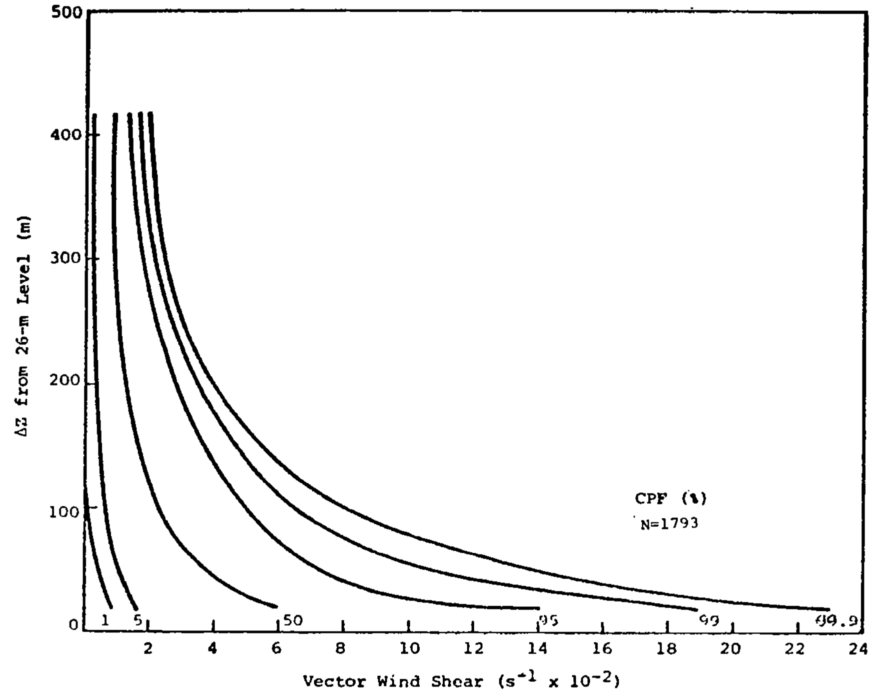


Fig. 7. Envelopes of vector wind shear for selected percentiles for tower data Set I between the 26-m level and higher levels.

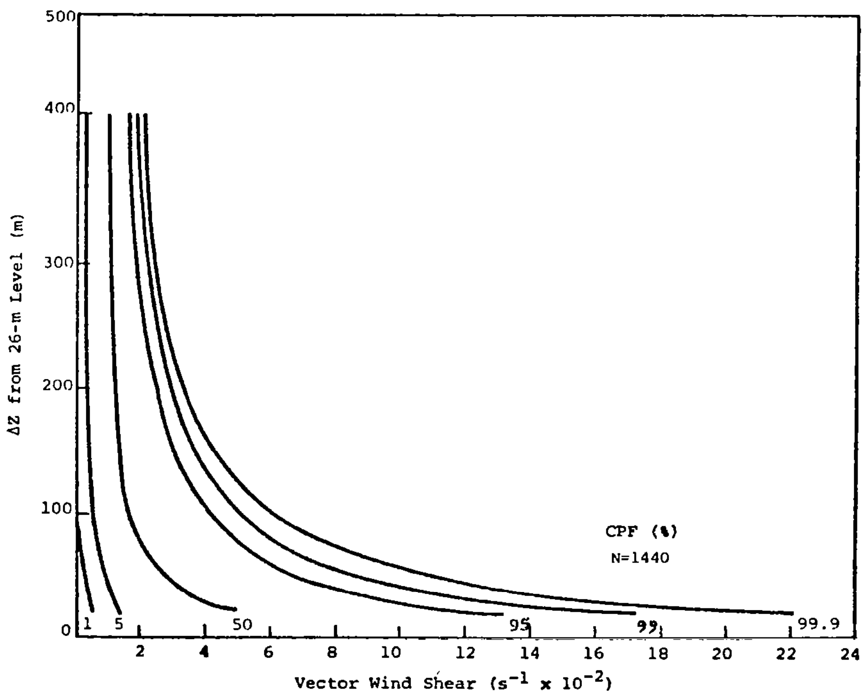


Fig. 8. Envelopes of vector wind shear for selected percentiles for tower data Set II between the 26-m level and higher levels.

CPF data for vector wind shear as a function of ΔZ from the top of the tower (444 m) to each lower level for data Sets I and II are presented in Figs. 9 and 10, respectively. In both figures, vector shears generally decreased with ΔZ, especially for the higher percentile levels. Vector wind shears ranged from about 1.5×10^{-2} s^{-1} to 4.4×10^{-2} s^{-1} at the 99 percentile level in Set I, while in Set II for the same percentile level the range was 1.7×10^{-2} s^{-1} to 3.8×10^{-2} s^{-1}.

Build-up vector wind change at various percentile values as a function of ΔZ (100 m - 1800 m) relative to heights ranging from 200 to 2000 m along all Jimsphere profiles were computed and the results for the 99 percentile values are given in Table III. Entries in the table are the vector wind changes (m s^{-1}) calculated over distances ΔZ listed along the top row below the height given in the left column.

Figure 11 is a graph of the vector shears computed from results in Table III. In the figure, vector shear (s^{-1}) is plotted as a function of height on the Jimsphere wind profiles for various vertical distances ranging from 100 to 1800 m identified on each curve.

Vectors shears were always larger for smaller ΔZ intervals at all heights along the Jimsphere profiles. The maximum vector shear was 0.0548 s^{-1} at the 200-m level (top of layer) over a ΔZ of 100 m, while the smallest shear was 0.00983 s^{-1} computed at the 2000-m level over a ΔZ of 1800 m. These data show for the 99 percentile level that vector shears over small ΔZ's are essentially independent of height except near the ground.

D. Wind direction change

In Figs. 12 and 13 are plotted the CPF data for wind direction change (sign included) (deg m^{-1}) as a function of ΔZ above 26 m for tower data Sets I and II, respectively. Both figures show a rapid decrease in the wind direction change for all percentile levels from the maximum values at the smallest ΔZ to ΔZ≃150 m, then a slow decrease as ΔZ becomes larger. Both figures also show a slightly higher probability that the wind direction change will be positive (veering), than negative (backing), especially for ΔZ<100 m, possibly indicating the average trend of wind direction change during the two synoptic situations.

The CPF data for the magnitude of direction change (deg m^{-1}) as a function of ΔZ from the 26-m level is shown in Figs. 14 and 15 for data Sets I and II, respectively. Again, magnitude changes in both figures show a rapid decrease at all percentile levels with an increase in ΔZ

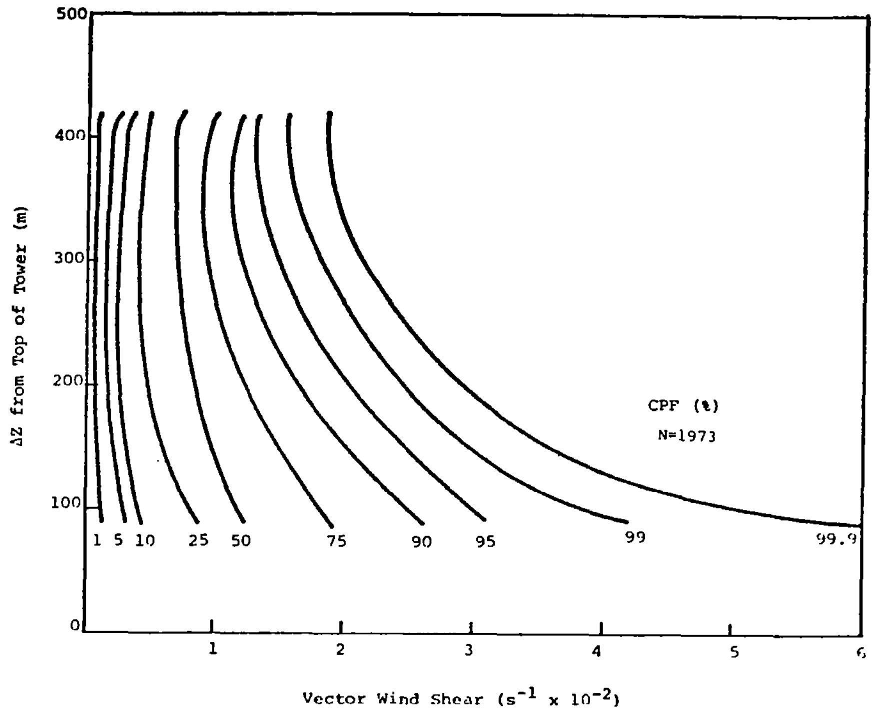


Fig. 9. Envelopes of vector wind shear for selected percentiles for tower data Set I between the 444-m level and lower levels.

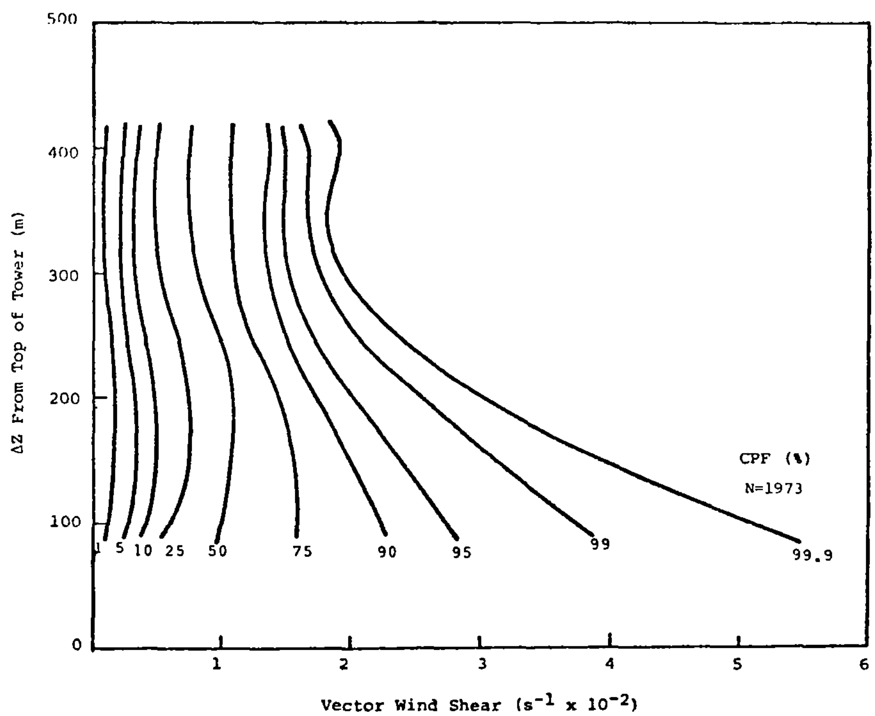


Fig. 10. Envelopes of vector wind shear for selected percentiles for tower data Set II between the 444-m level and lower levels.

TABLE III

Jimsphere vector wind change envelopes (99 percentile) as a function of height of top of layers (m s^{-1})

Height of top of layers (m)	Height interval (m)									
	1800	1600	1400	1200	1000	800	600	400	200	100
200	-	-	-	-	-	-	-	-	-	5.48
400	-	-	-	-	-	-	-	-	6.47	3.96
600	-	-	-	-	-	-	-	10.07	5.97	3.46
800	-	-	-	-	-	-	12.61	9.64	5.63	3.40
1000	-	-	-	-	-	14.69	12.63	9.63	5.94	3.68
1200	-	-	-	-	15.73	14.31	12.47	9.95	6.28	3.41
1400	-	-	-	16.76	15.73	14.39	12.58	9.57	5.66	3.67
1600	-	-	18.26	17 18	16.03	14.27	11.99	9.12	6.09	3.48
1800	-	19.42	18.34	17.92	15.74	13.85	10.95	8.83	5.29	3.45
2000	19.67	18.99	18.83	17.03	15.35	12.68	11.04	8.70	5.72	3.49

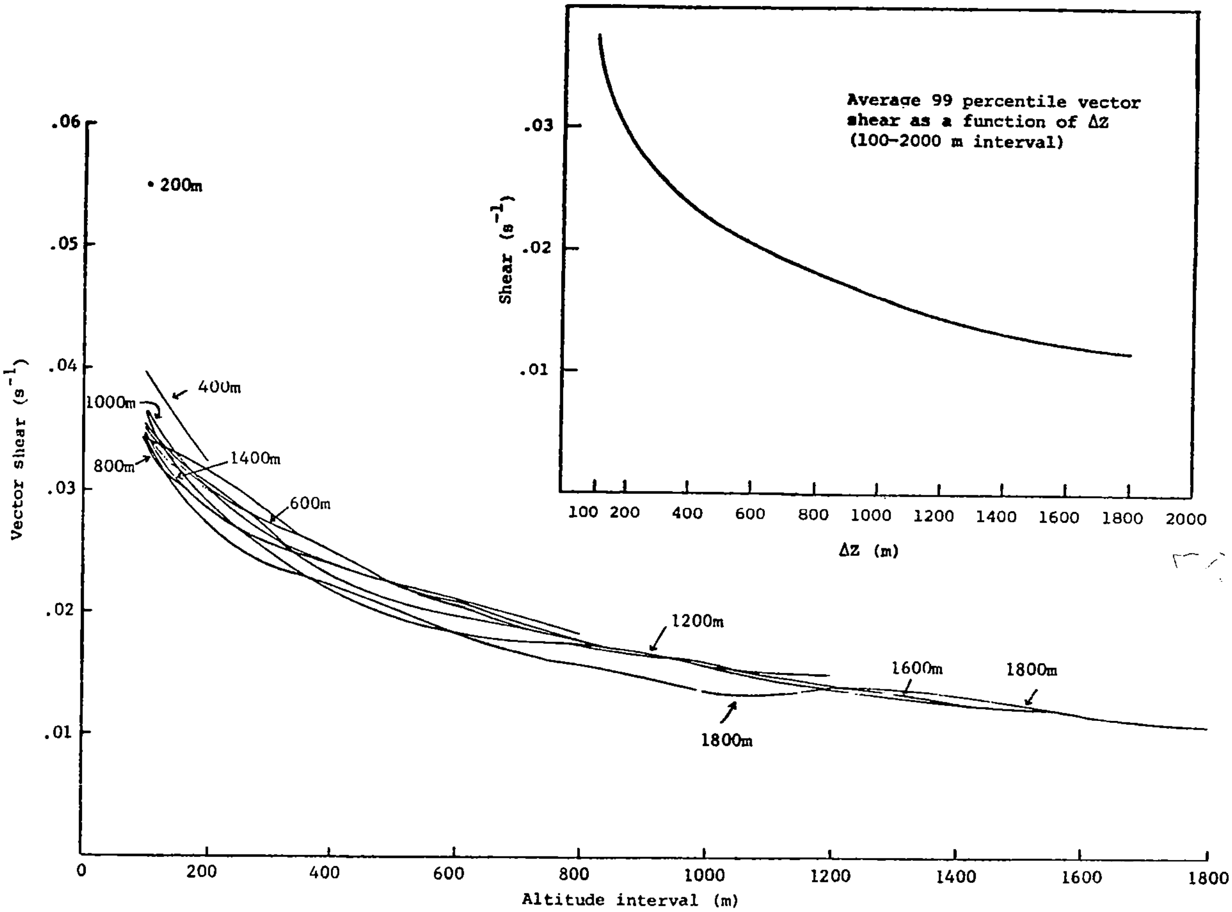


Fig. 11. Envelopes of vector wind shear (99 percentile) prepared from Table III.

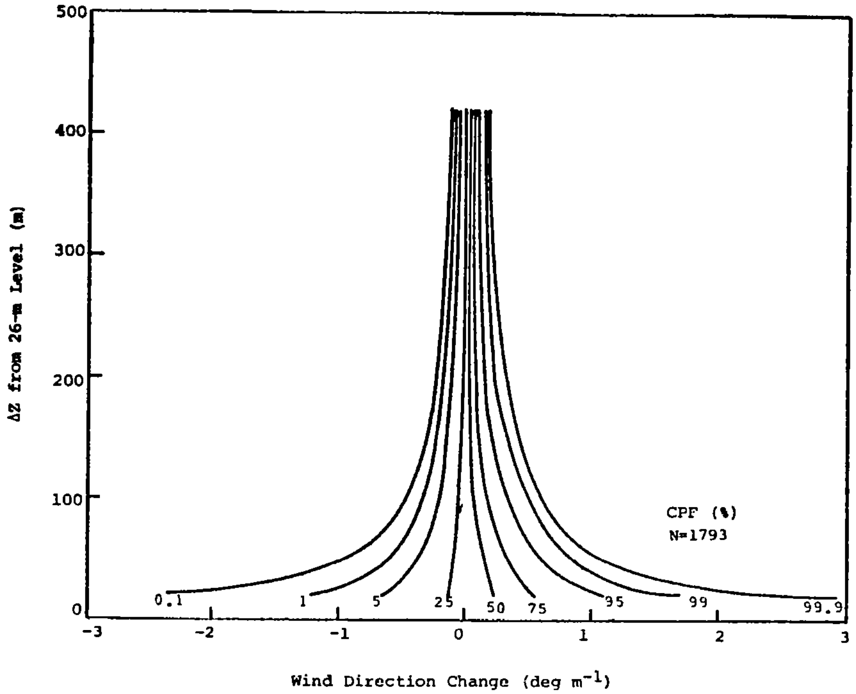


Fig. 12. Envelopes of wind direction change for selected percentiles for tower data Set I between the 26-m level and higher levels.

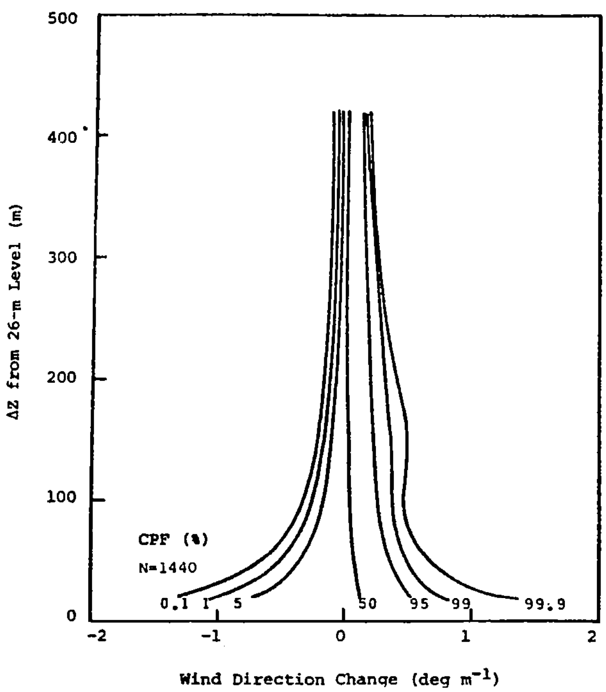


Fig. 13. Envelopes of wind direction change for selected percentiles for tower data Set II between the 26-m level and higher levels.

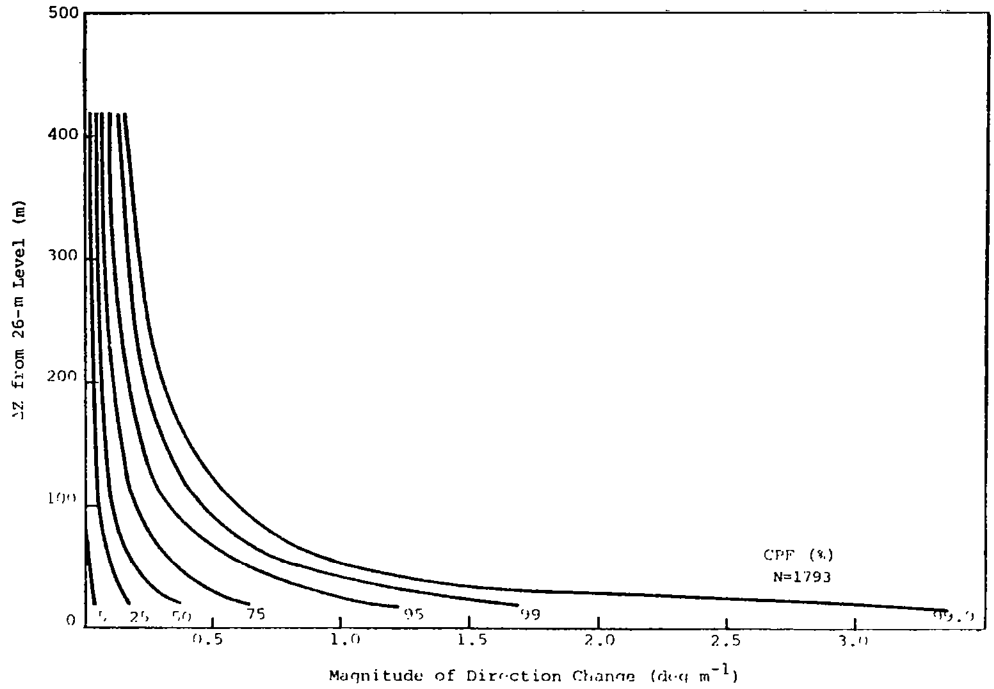


Fig. 14. Envelopes of the magnitude of wind direction change for selected percentiles for tower data Set I between the 26-m level and higher levels.

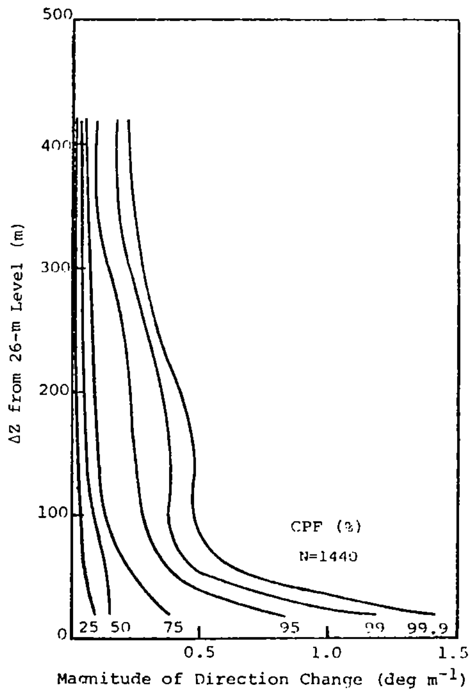


Fig. 15. Envelopes of the magnitude of wind direction change for selected percentiles for tower data Set II between the 26-m level and higher levels.

for $\Delta Z<150$ m, then a slow decrease as ΔZ increases. Considering the range of direction change in Fig. 14, a 1% probability exists for the magnitude of the direction change to exceed about 1.7 deg m^{-1} for the smallest ΔZ, and decreases to about 0.2 deg m^{-1} for the largest ΔZ. In Fig. 15, a slightly smaller range of direction change was computed at the same probability level.

E. <u>Gust Factor as a function of averaging time interval and height</u>

Figure 16 shows the gust factor computed from tower data Set I using all tower levels from 26 m to 444 m as a function of averaging time interval from 0.5 min to 30 min. For all averaging time intervals, the gust factor decreased with increasing height. At 26 m, gust factors ranged from about 1.20 to 1.80 between averaging intervals of 0.5 min and 30 min, respectively, while at 444 m the gust factor ranged from about 1.10 to 1.38 over the same averaging periods. The largest range of gust factors occurred at 26 m, and the minimum range at 444 m. The decrease with height of the gust factor from 26 m to 444 m is smallest for short averaging periods and largest for long averaging periods. The decrease with height varies from approximately 0.30 to 0.47 as the averaging interval varies between 5 and 30 min, respectively.

F. <u>Spectra of component winds</u>

Normalized spectra of the component winds for various heights (26, 45, 90, 177, 266, 355, and 444 m) of tower data Set I are shown in Fig. 17. The wind direction was such that tower interference should not have been significant; therefore, tower interference was not considered in the computation of spectra. At each level, component wind spectra were computed along the eight axes orientations listed in the upper right of the figure with the total variance and mean wind component along each axis listed in the lower left of the figure.

At all levels, the fraction of the total variance contained in the longer-period harmonics is dominant with a logrithmic decrease in the fraction of the total variance with a logrithmic increase in frequency. The differences in the spectra at a given level are small, indicating the existence of nearly isotropic eddies for all eddy sizes. In addition, little difference in the normalized spectra along the various axes was found at any level, indicating nearly isotropic eddies at all heights from 26 m up to 444 m. However, a decrease with height in the total energy was observed.

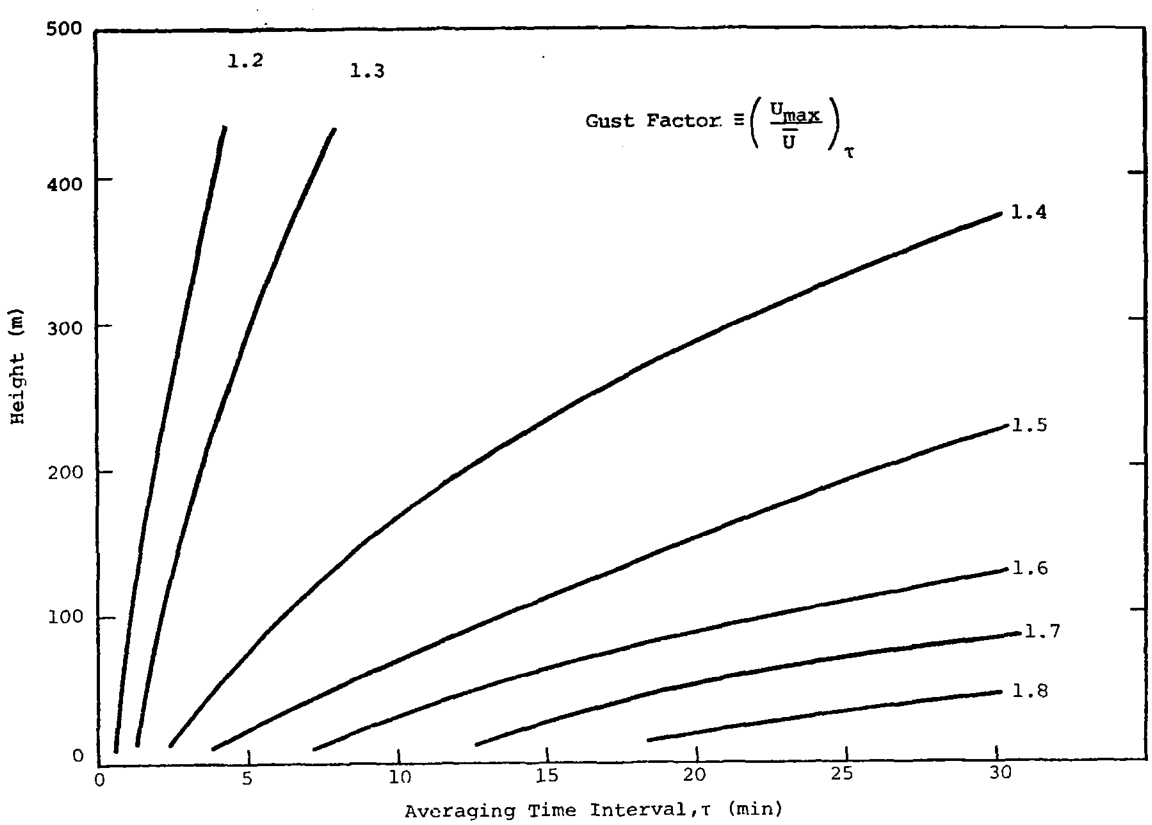


Fig. 16. Gust factor as function of height and averaging interval for tower data Set I.

for $\Delta Z<150$ m, then a slow decrease as ΔZ increases. Considering the range of direction change in Fig. 14, a 1% probability exists for the magnitude of the direction change to exceed about 1.7 deg m^{-1} for the smallest ΔZ, and decreases to about 0.2 deg m^{-1} for the largest ΔZ. In Fig. 15, a slightly smaller range of direction change was computed at the same probability level.

E. Gust Factor as a function of averaging time interval and height

Figure 16 shows the gust factor computed from tower data Set I using all tower levels from 26 m to 444 m as a function of averaging time interval from 0.5 min to 30 min. For all averaging time intervals, the gust factor decreased with increasing height. At 26 m, gust factors ranged from about 1.20 to 1.80 between averaging intervals of 0.5 min and 30 min, respectively, while at 444 m the gust factor ranged from about 1.10 to 1.38 over the same averaging periods. The largest range of gust factors occurred at 26 m, and the minimum range at 444 m. The decrease with height of the gust factor from 26 m to 444 m is smallest for short averaging periods and largest for long averaging periods. The decrease with height varies from approximately 0.30 to 0.47 as the averaging interval varies between 5 and 30 min, respectively.

F. Spectra of component winds

Normalized spectra of the component winds for various heights (26, 45, 90, 177, 266, 355, and 444 m) of tower data Set I are shown in Fig. 17. The wind direction was such that tower interference should not have been significant; therefore, tower interference was not considered in the computation of spectra. At each level, component wind spectra were computed along the eight axes orientations listed in the upper right of the figure with the total variance and mean wind component along each axis listed in the lower left of the figure.

At all levels, the fraction of the total variance contained in the longer-period harmonics is dominant with a logrithmic decrease in the fraction of the total variance with a logrithmic increase in frequency. The differences in the spectra at a given level are small, indicating the existence of nearly isotropic eddies for all eddy sizes. In addition, little difference in the normalized spectra along the various axes was found at any level, indicating nearly isotropic eddies at all heights from 26 m up to 444 m. However, a decrease with height in the total energy was observed.

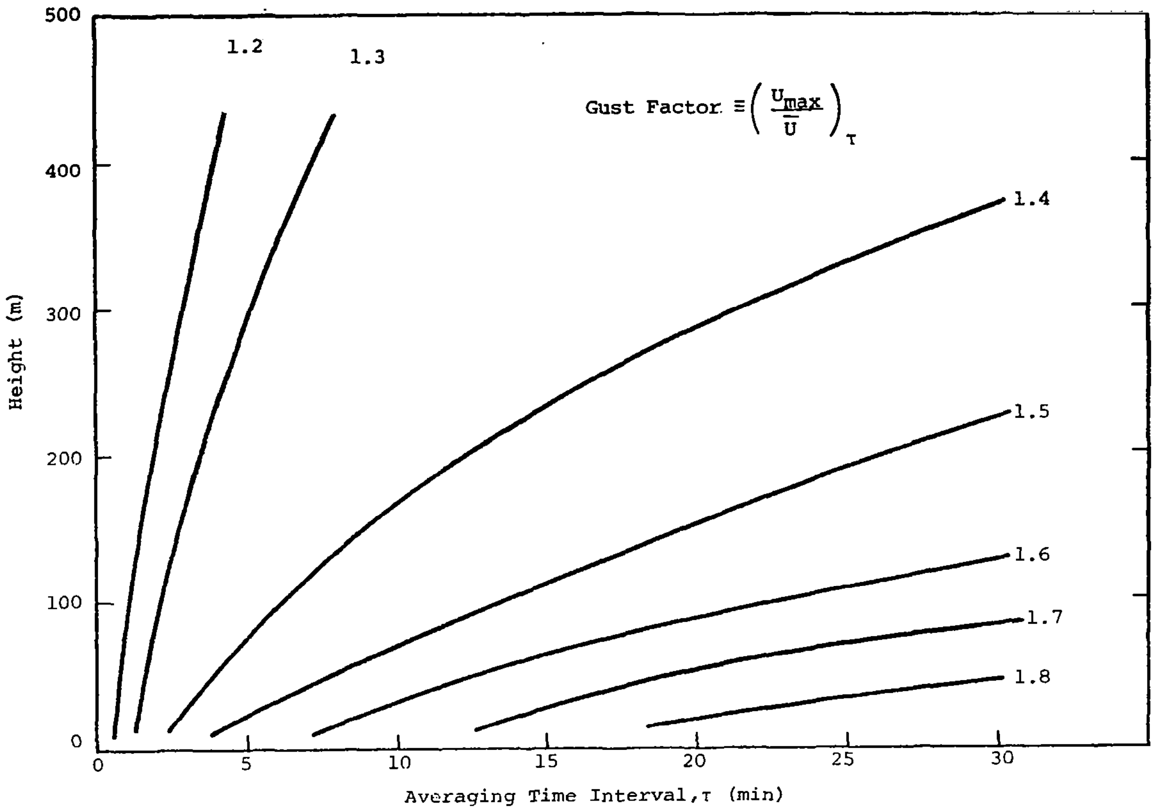
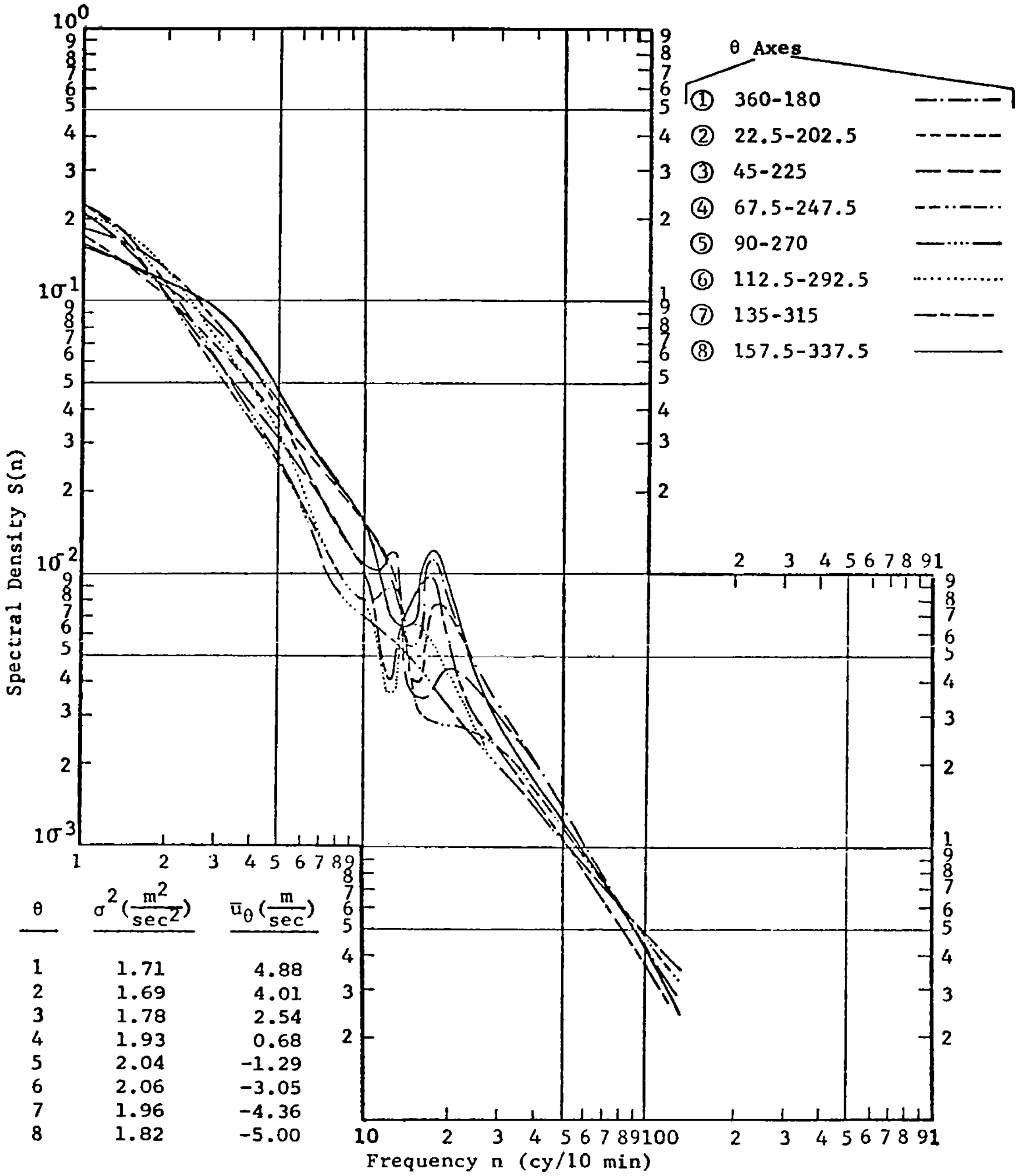


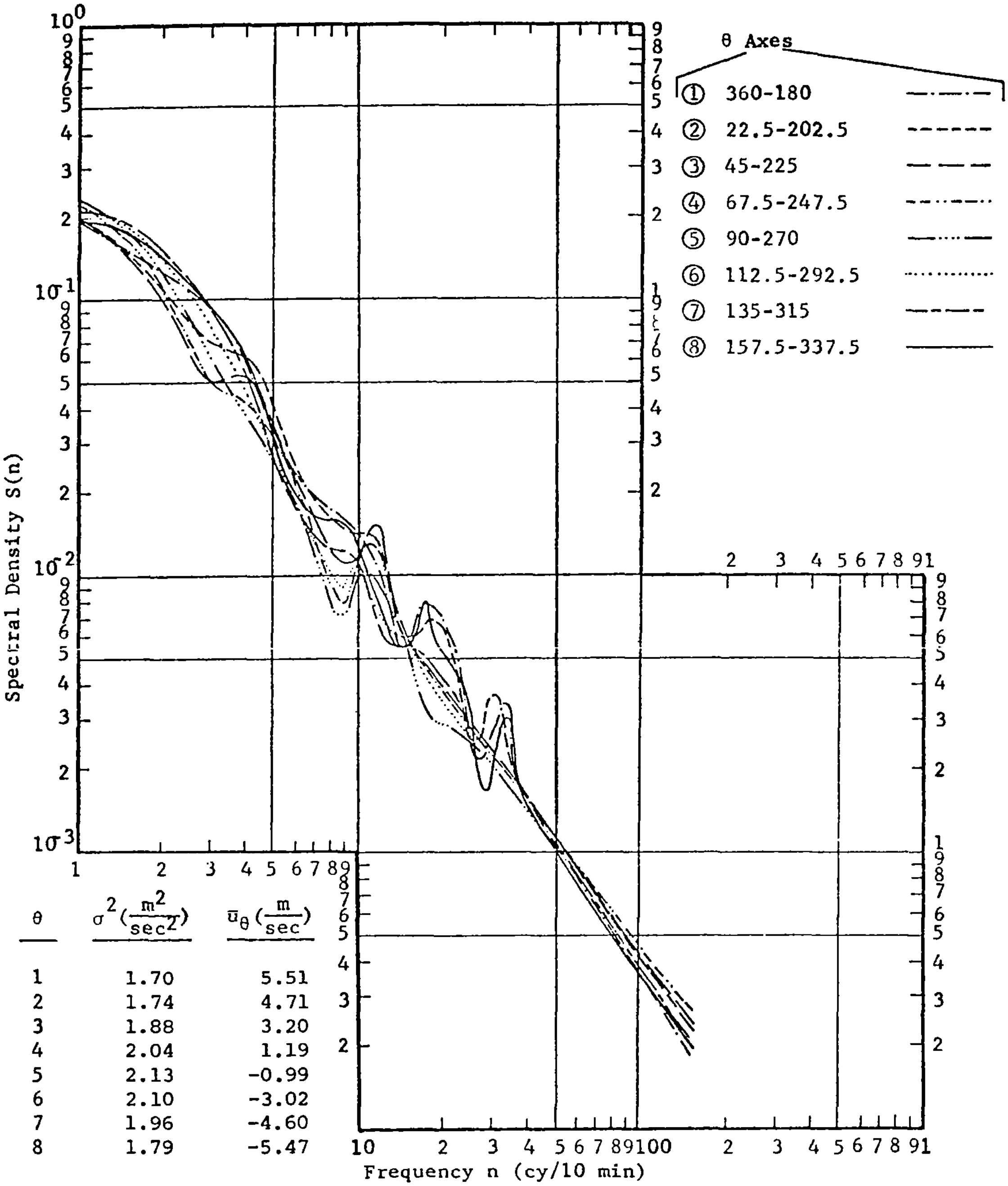
Fig. 16. Gust factor as function of height and averaging interval for tower data Set I.



θ	$\sigma^2 (\frac{m^2}{sec^2})$	$\bar{u}_\theta (\frac{m}{sec})$
1	1.71	4.88
2	1.69	4.01
3	1.78	2.54
4	1.93	0.68
5	2.04	-1.29
6	2.06	-3.05
7	1.96	-4.36
8	1.82	-5.00

a) Height - 26 m

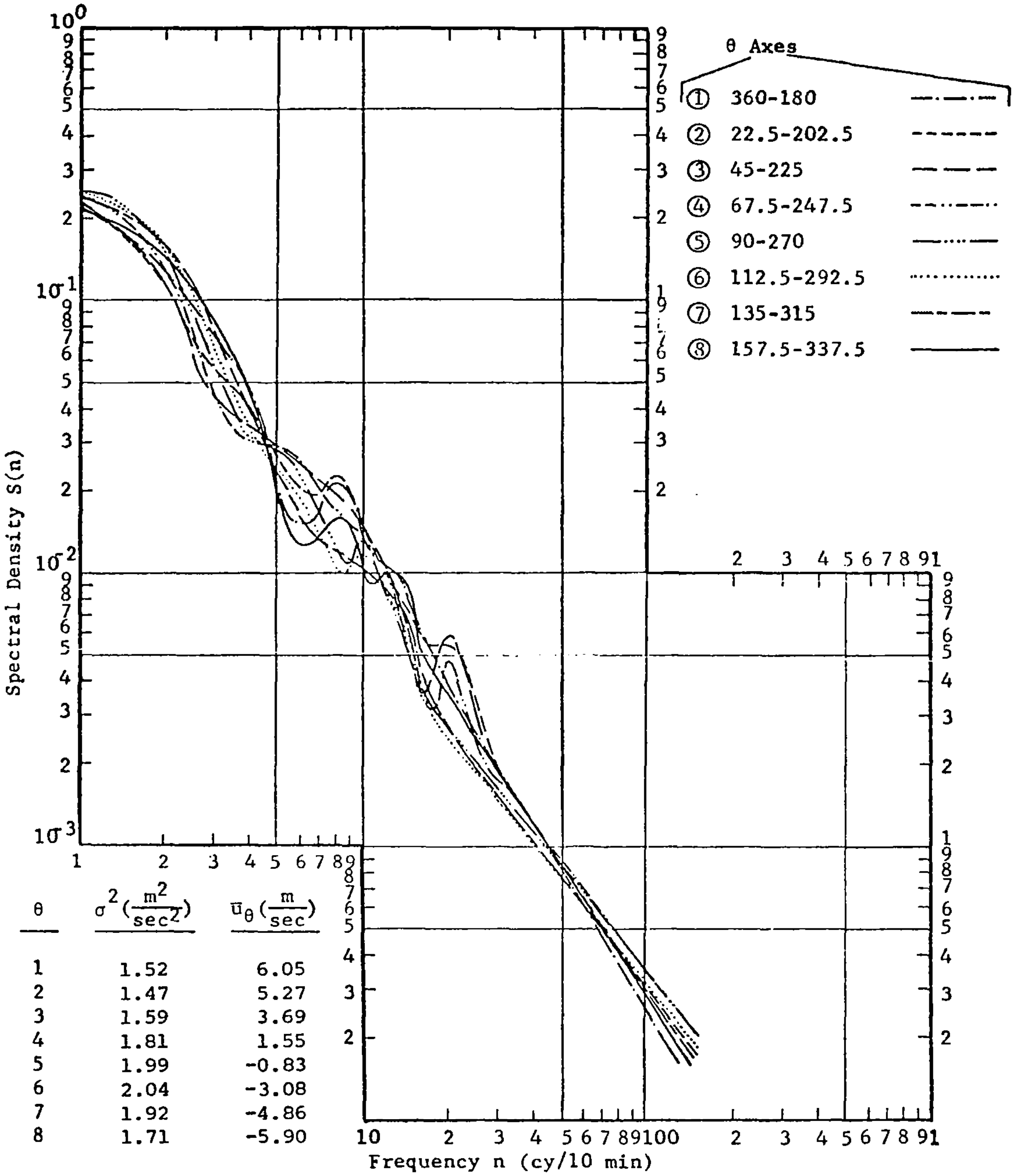
Fig. 17. Normalized spectra along selected axes (azimuths) for each data level for tower data Set I.



θ	$\sigma^2 (\frac{m^2}{sec^2})$	$\bar{u}_\theta (\frac{m}{sec})$
1	1.70	5.51
2	1.74	4.71
3	1.88	3.20
4	2.04	1.19
5	2.13	-0.99
6	2.10	-3.02
7	1.96	-4.60
8	1.79	-5.47

b) Height - 45 m

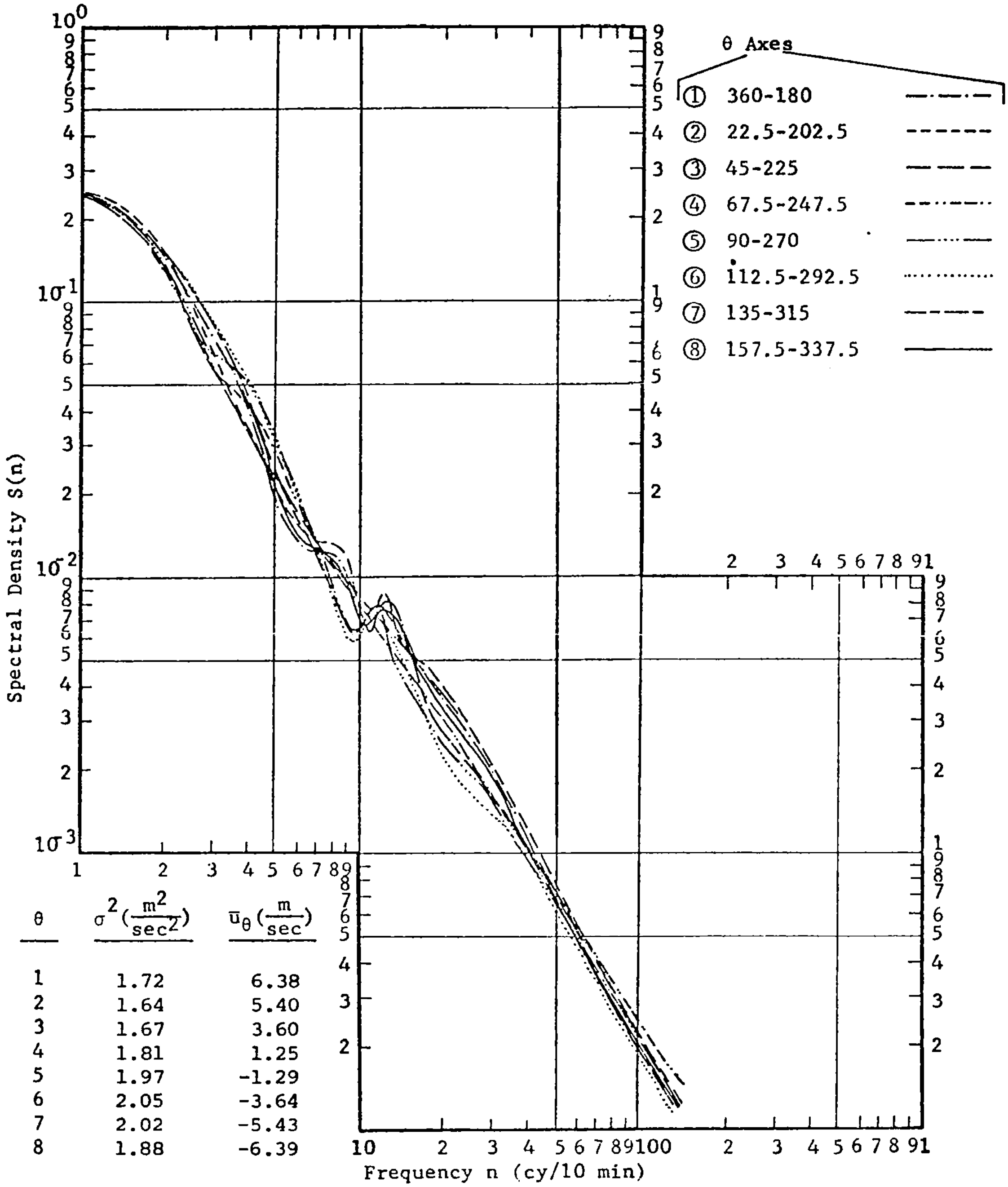
Fig. 17. (Continued)



θ	$\sigma^2 (\frac{m^2}{sec^2})$	$\bar{u}_\theta (\frac{m}{sec})$
1	1.52	6.05
2	1.47	5.27
3	1.59	3.69
4	1.81	1.55
5	1.99	-0.83
6	2.04	-3.08
7	1.92	-4.86
8	1.71	-5.90

c) Height - 90 m

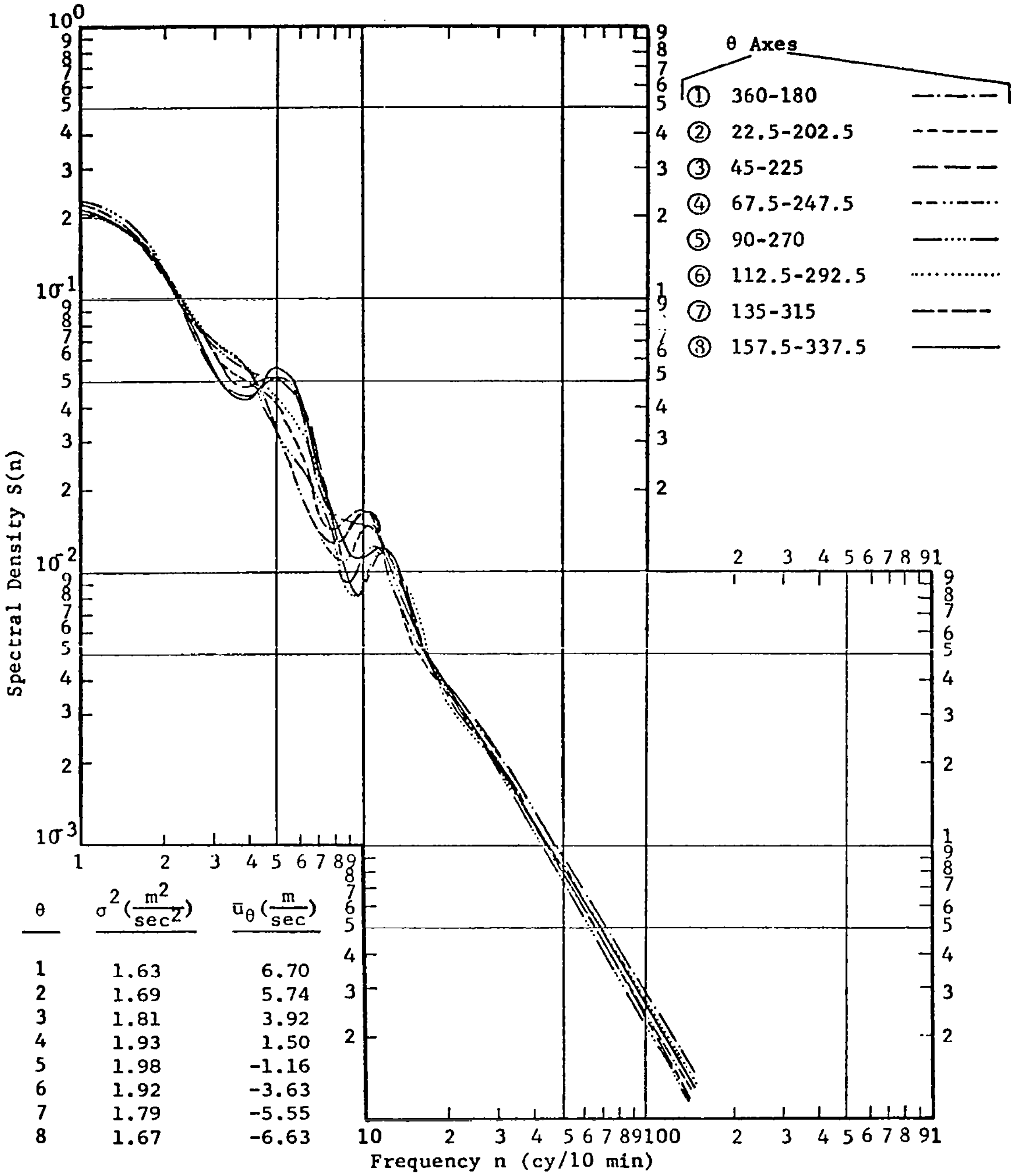
Fig. 17. (Continued)



θ	$\sigma^2 (\frac{m^2}{sec^2})$	$\bar{u}_\theta (\frac{m}{sec})$
1	1.72	6.38
2	1.64	5.40
3	1.67	3.60
4	1.81	1.25
5	1.97	-1.29
6	2.05	-3.64
7	2.02	-5.43
8	1.88	-6.39

d) Height - 177 m

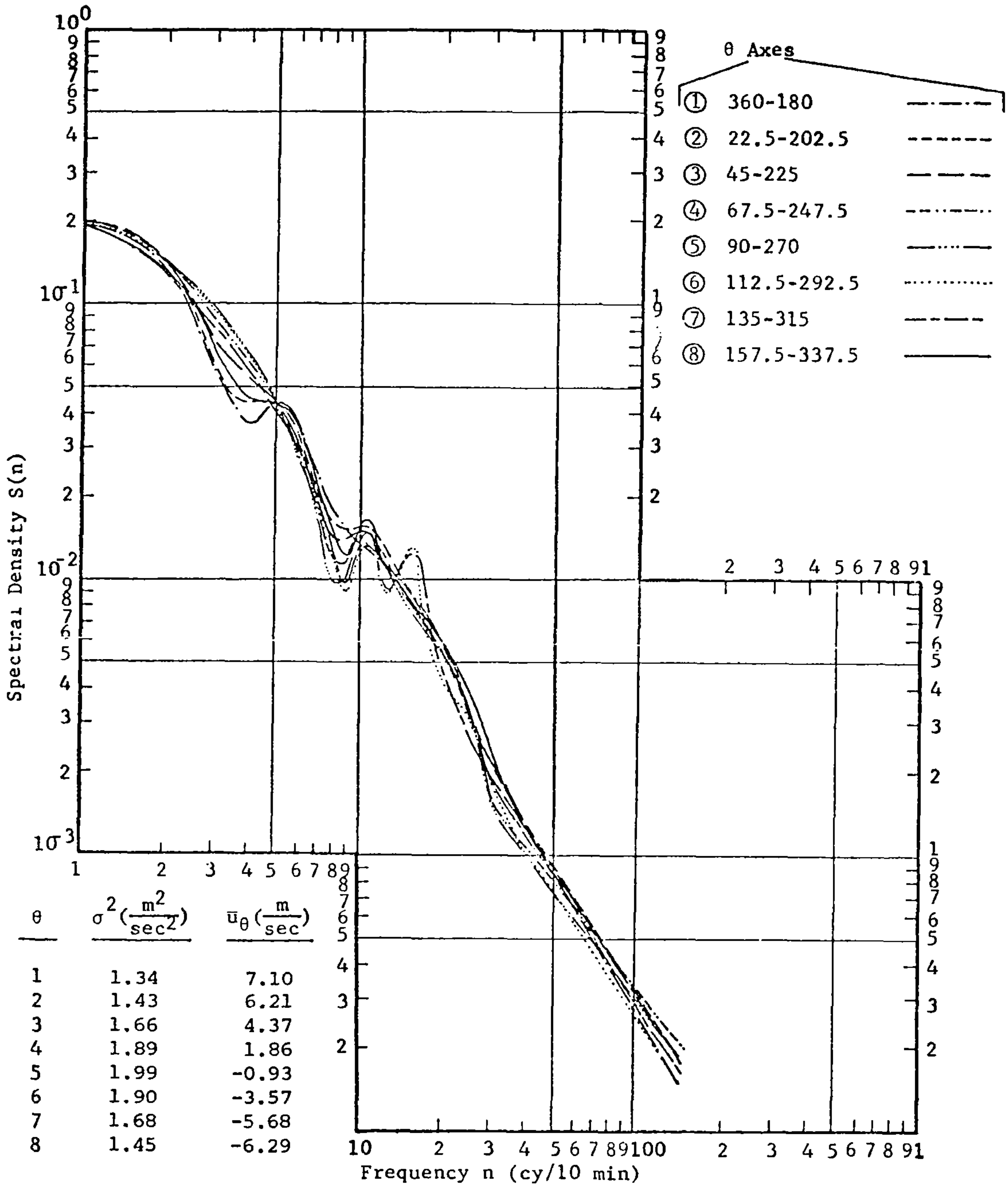
Fig. 17. (Continued)



θ	$\sigma^2 (\frac{m^2}{sec^2})$	$\bar{u}_\theta (\frac{m}{sec})$
1	1.63	6.70
2	1.69	5.74
3	1.81	3.92
4	1.93	1.50
5	1.98	-1.16
6	1.92	-3.63
7	1.79	-5.55
8	1.67	-6.63

e) Height - 266 m

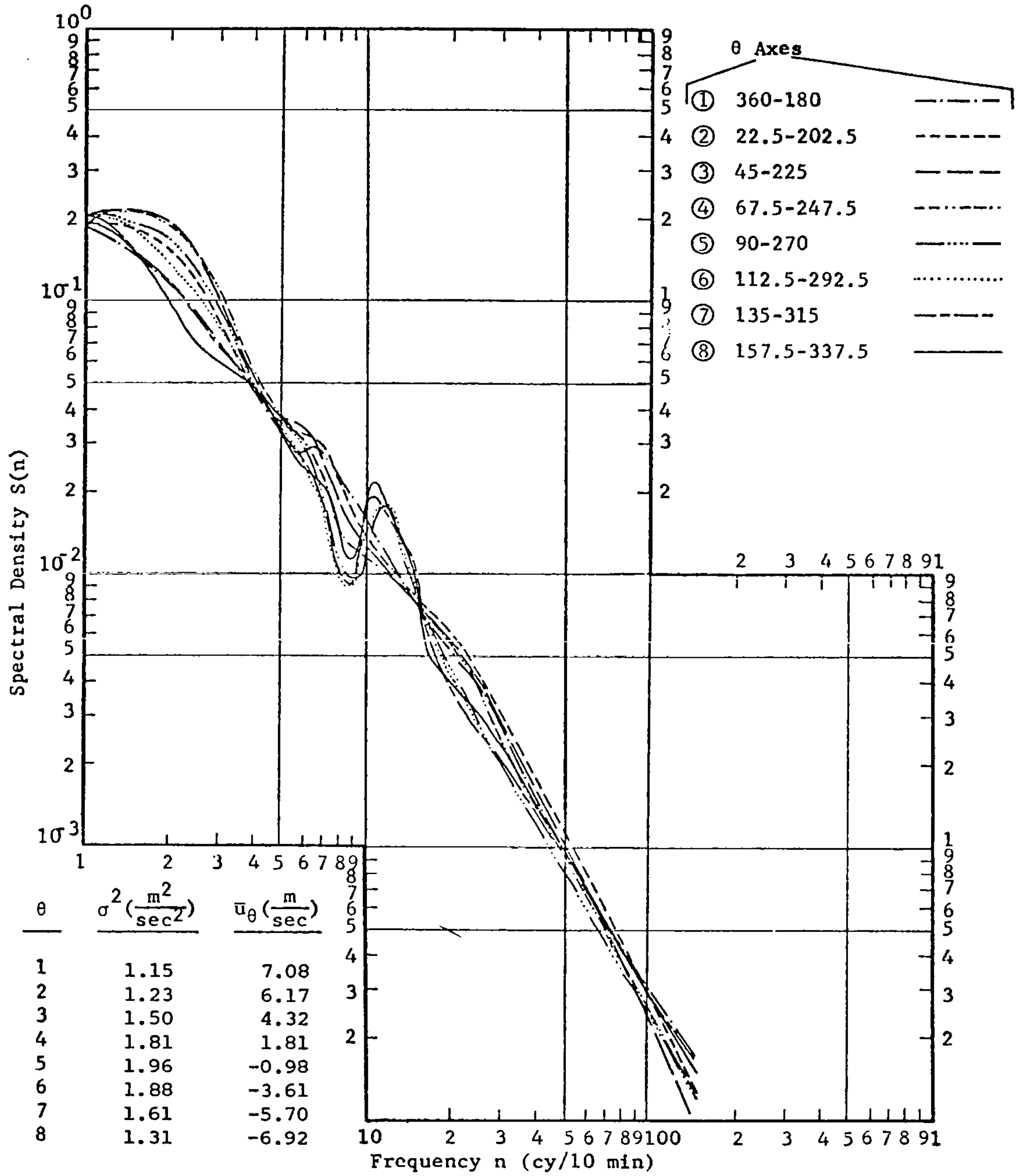
Fig. 17. (Continued)



θ	$\sigma^2 (\frac{m^2}{sec^2})$	$\bar{u}_\theta (\frac{m}{sec})$
1	1.34	7.10
2	1.43	6.21
3	1.66	4.37
4	1.89	1.86
5	1.99	-0.93
6	1.90	-3.57
7	1.68	-5.68
8	1.45	-6.29

f) Height - 355 m

Fig. 17. (Continued)



θ	$\sigma^2\left(\frac{m^2}{sec^2}\right)$	$\bar{u}_\theta\left(\frac{m}{sec}\right)$
1	1.15	7.08
2	1.23	6.17
3	1.50	4.32
4	1.81	1.81
5	1.96	-0.98
6	1.88	-3.61
7	1.61	-5.70
8	1.31	-6.92

g) Height - 444 m

Fig. 17. (Continued)

4. CONSIDERATIONS FOR UNIFYING GROUND AND INFLIGHT WIND CRITERIA

A comparison between the established design wind criteria (Daniels, 1973) and the results obtained from the tower and Jimsphere data is presented in this section for the layer from the surface to 2000 m. Emphasis is placed on the reevaluation of some existing design wind criteria in the region between the ground and inflight criteria (150-1000 m), and on a method for merging the two sets of criteria based on results presented above.

A. Steady state and directional vertical wind profiles

Currently accepted Space Shuttle design wind criteria specifies a nondirectional (five percent risk) steady state wind speed profile from the surface up to 150 m*. Directional inflight wind profile envelopes (95th percentile) for different flight azimuths down to 1 km are given by Daniels (1973). The solid segments of curves S, A, B, C, and D in Figs. 18 through 20, which extend up to 150 m, represent the nondirectional 95th percentile ground wind design steady state wind profiles. The solid segment of curve S in Fig. 18, which extends above 1000 m, is the 95th percentile inflight scalar wind speed steady state profile, while the solid segments, above 1000 m, of curves A, B, C, and D in Figs. 19 and 20 are the directional 95th percentile inflight wind profiles for a head wind, tail wind, right crosswind, and left crosswind along the indicated flight azimuths.

In order to establish directional and nondirectional design vertical wind profiles between 150 and 1000 m, it is necessary to develop a consistent and reasonable technique for merging these two established wind criteria. Therefore, the Jimsphere vertical wind profiles were used as the primary data source for the development of wind profile conditions in this layer. Because of the limited extent of this data sample as compared with the data sets used to establish the criteria presented by Daniels, the results will be used to establish trends rather than exact criteria. Existing criteria will not be altered.

In Fig. 18, curve S' is the 95th percentile Jimsphere scalar steady state wind speed profile taken from Fig. 4, while curves A', B', C', and D' in Figs. 19 and 20 are the 95th percentile directional wind speed profiles

* Appendix 10.10, Natural Environment Design Requirements, "Space Shuttle Document," Vol. X, March 1974.

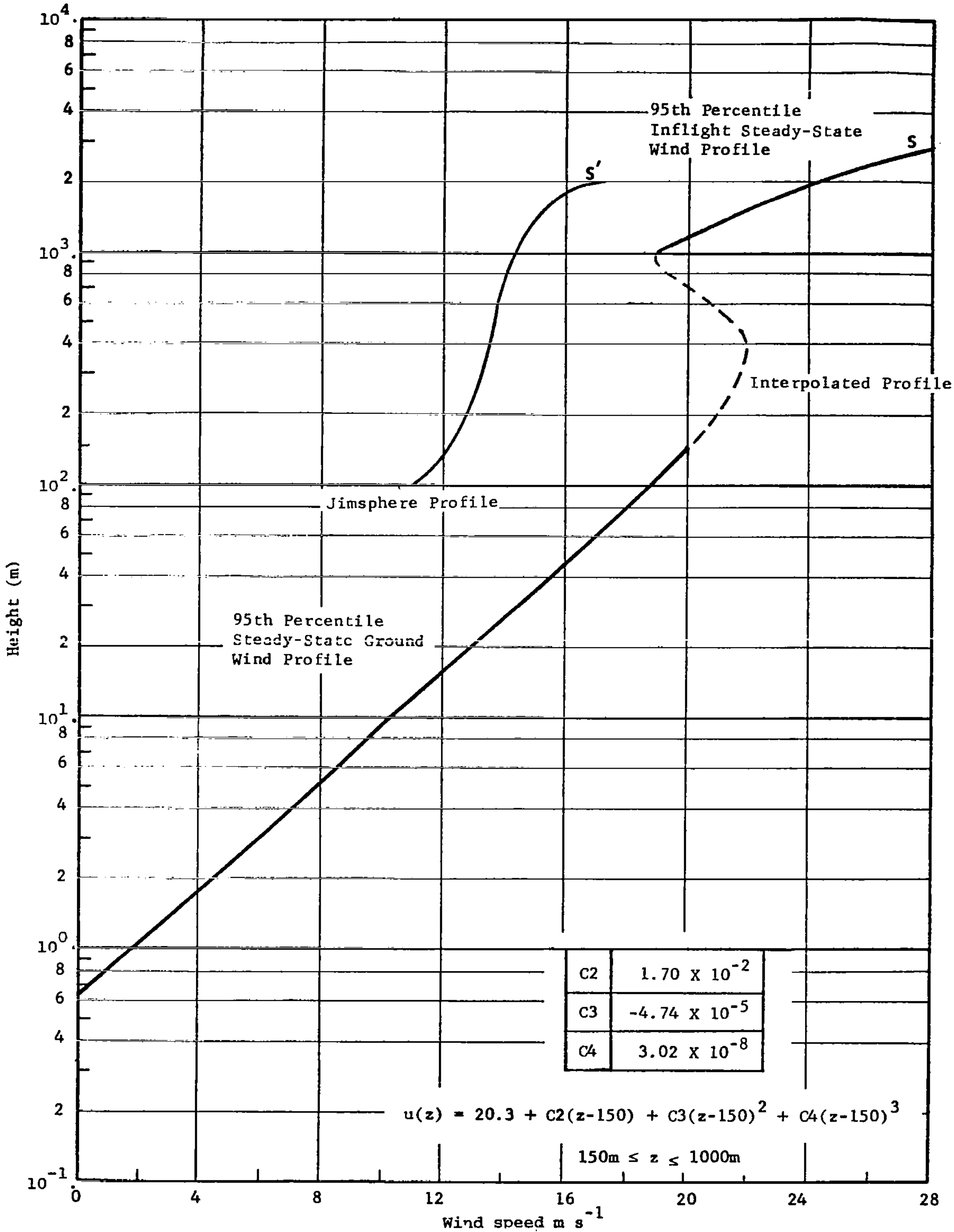
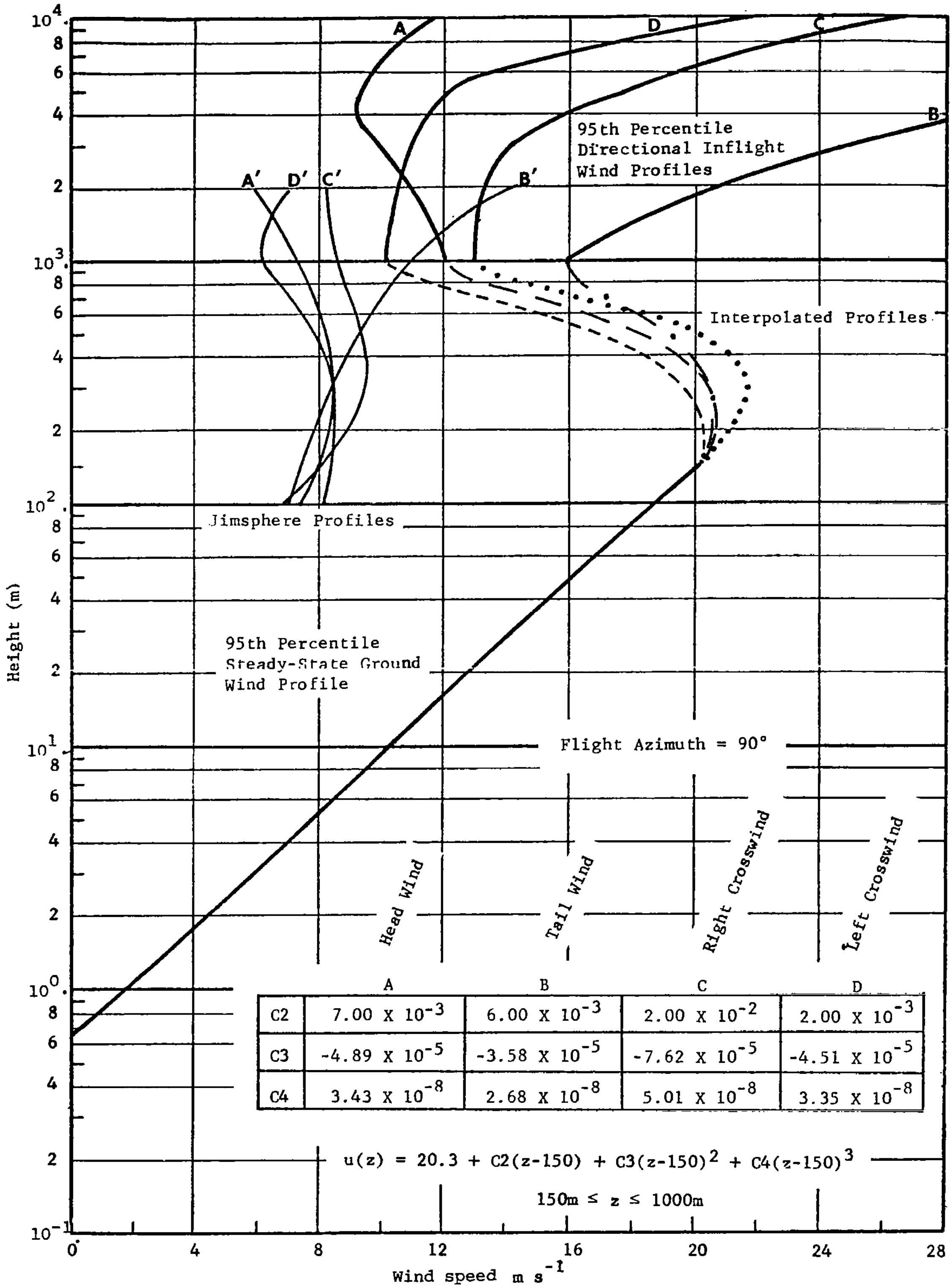


Fig. 18. Unified 95 percentile steady state wind speed profile envelope.

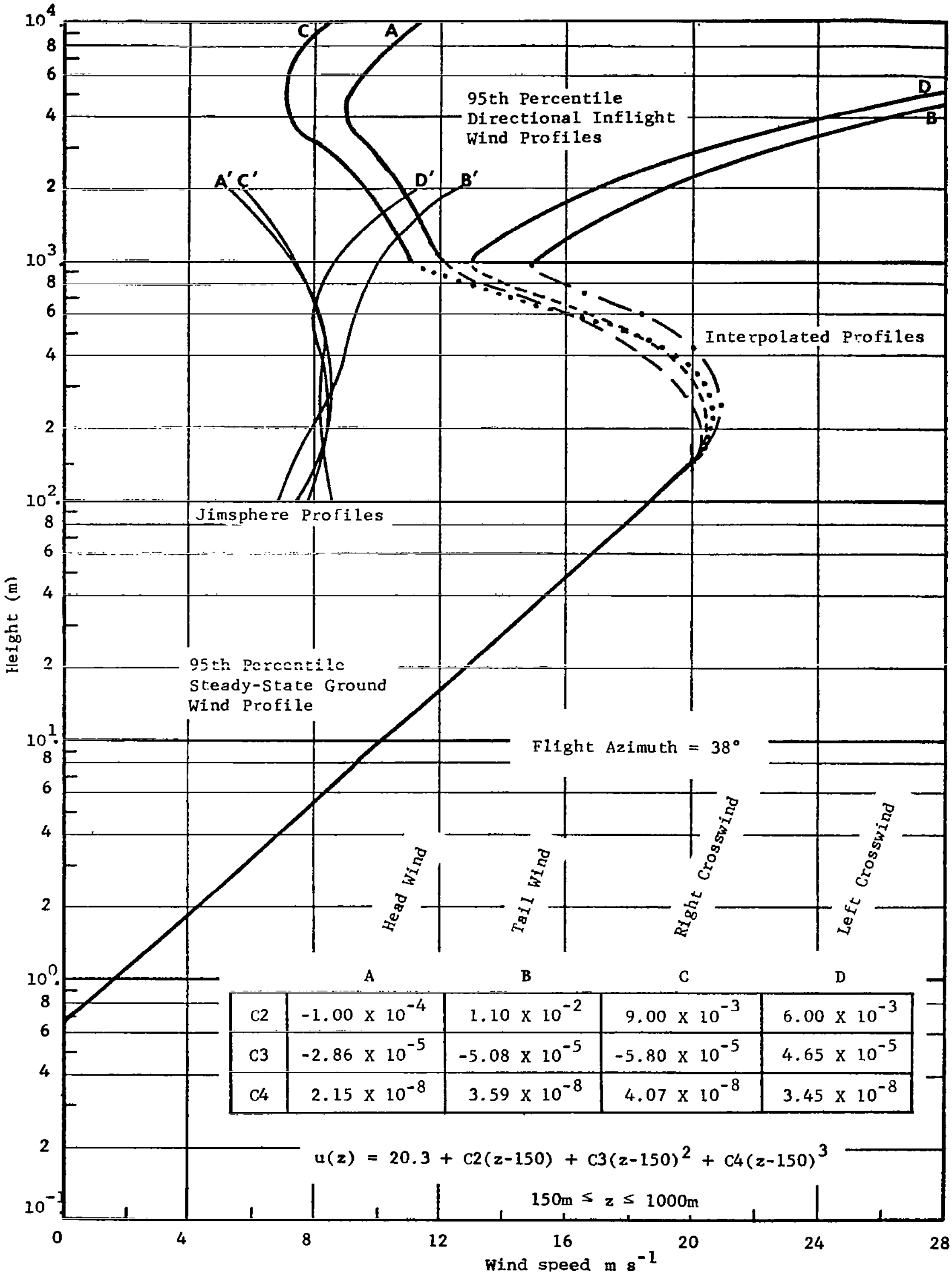


	A	B	C	D
C2	7.00×10^{-3}	6.00×10^{-3}	2.00×10^{-2}	2.00×10^{-3}
C3	-4.89×10^{-5}	-3.58×10^{-5}	-7.62×10^{-5}	-4.51×10^{-5}
C4	3.43×10^{-8}	2.68×10^{-8}	5.01×10^{-8}	3.35×10^{-8}

$$u(z) = 20.3 + C2(z-150) + C3(z-150)^2 + C4(z-150)^3$$

$$150\text{m} \le z \le 1000\text{m}$$

Fig. 19. Unified 95 percentile directional steady state wind speed profile envelopes for flight azimuth of 90 degrees.



	A	B	C	D
C2	-1.00×10^{-4}	1.10×10^{-2}	9.00×10^{-3}	6.00×10^{-3}
C3	-2.86×10^{-5}	-5.08×10^{-5}	-5.80×10^{-5}	4.65×10^{-5}
C4	2.15×10^{-8}	3.59×10^{-8}	4.07×10^{-8}	3.45×10^{-8}

$$u(z) = 20.3 + C2(z-150) + C3(z-150)^2 + C4(z-150)^3$$

$$150\text{m} \le z \le 1000\text{m}$$

Fig. 20. Unified 95 percentile directional steady state wind speed profile envelopes for flight azimuth of 38 degrees.

for a head wind, tail wind, right crosswind, and left crosswind, respectively, for the indicated flight azimuths of 90° and 38°. The directional wind profiles were interpolated from the directional wind component envelopes at the 20 levels along the Jimsphere profiles (100-2000 m) shown in Fig. 6.

In using the Jimsphere profiles to connect the ground and inflight wind criteria, the Jimsphere profile wind speed magnitudes were always found to be less than the established design wind speeds in the overlapping intervals between 100-150 m and 1000-2000 m as seen in Figs. 18-20. One probable reason for the differences in wind speeds is that the established design profiles were obtained from a large climatological data set (≃10K observations) while the Jimsphere profiles were computed from a much smaller data set (≃4K observations).

Even so, the general shapes of the Jimsphere profiles should be representative of the overall behavior of wind speed profiles through the boundary layer for given percentile levels. Therefore, the shapes of the Jimsphere 95th percentile profiles (both steady state and directional) were used as a guide to merge the two wind criteria, while the wind speed magnitudes for both the established ground and inflight criteria were not changed. The validity of using only the shape and ignoring the wind speed magnitudes of the Jimsphere data is supported by the fact that the slopes of both the established ground and inflight wind criteria and the Jimsphere profiles are similar, especially in the 100-300 m and 1000-2000 m layers where the merging is accomplished.

To incorporate the general shape of the Jimsphere profiles between the two accepted wind speeds at 150 m and 1000 m, a cubic spline curve-fitting procedure was used (Conte and de Boor, 1965). This procedure interpolates a third degree polynomial between two points using either calculated or approximated curve slopes (first derivatives) at the two end points. Since N+1 degrees of freedom are needed to establish an Nth degree polynomial curve fit, the curve slopes and wind speed values at the two end points give 4 degrees of freedom and allow a 3rd degree interpolating polynomial to be computed. Therefore, the slopes at the 150- and 1000-m levels on the Jimsphere profiles were approximated by simple finite differences $(\frac{\Delta |\vec{V}|}{\Delta Z})$ and the wind speed magnitudes at the same levels on the ground and inflight wind criteria were used as the end points.

Broken, dashed, or dotted lines in Figs. 18-20 are plots of the cubic spline interpolating polynomials for the 95th percentile steady state and directional wind speed profiles along the indicated curve in each figure. The general form of each cubic spline is

$$u(z) = 20.3 + C2(z-150) + C3(z-150)^2 + C4(z-150)^3$$

where u is a function of height z (150m<z<1000m), and C2, C3, and C4 are calculated constants. The three constants for each cubic spline for the indicated design wind profile are ,presented in the figures.

The resulting interpolated design wind profiles provide a smooth and somewhat continuous connection between inflight and ground wind criteria based on the shape of wind profiles indicated by Jimsphere data. The interpolated profiles between 150 and 400 m appear almost logarithmic through the upper zone of the friction layer which was observed by Maas and Scoggins (1976) in their analysis of this same NSSL tower data.

B. Wind shears and synthetic wind profiles without gusts

The design synthetic wind profiles are computed from a combination of reference height design wind and the associated shear envelope (Daniels, 1973).

The currently accepted synthetic wind profile for a 95 percentile steady state wind profile starting at the 2000-m level is shown in Fig. 21 as curve Y. This synthetic profile was computed from the 99 percentile build-up shear given by Daniels (1973) where values of build-up shears were interpolated for the 24 m s^{-1} wind speed at 2000 m. Curve Y extends only down to 1000 m where the established synthetic profiles end.

The Jimsphere 99 percentile build-up shears in Table III were used with the 95 percentile steady state wind profile shown in Fig. 18 to construct synthetic wind profiles for various heights (200-2000 m). A comparison between the accepted (curve Y) and computed synthetic wind profiles starting at 2000 m reveals little difference relative to either

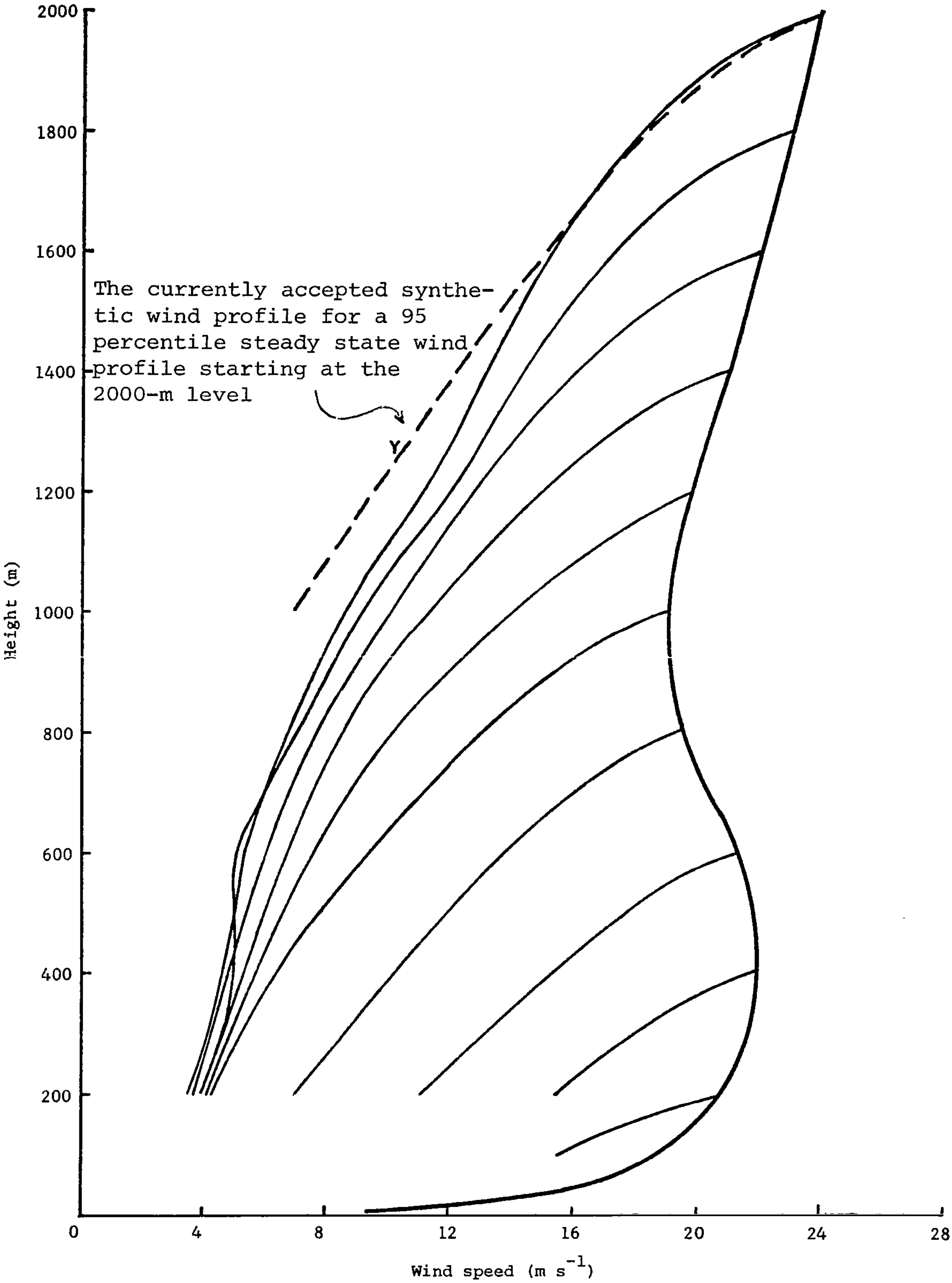


Fig. 21. Synthetic wind profiles constructed from 99 percentile shears (wind speed changes) and the 95 percentile steady state wind speed envelope.

the shape or magnitude of the profiles. The maximum wind speed difference is at 1000 m where only a 1 m s^{-1} difference occurs. In addition, there is little difference between any of the Jimsphere synthetic profiles building up to the steady state profile at or above 600 m. Therefore, the build-up shears for heights above about 600 m and ranging over ΔZ intervals from 100 to 1800 m are very similar. Plots of these shears in Fig. 11 show this more clearly.

If all the 99 percentile Jimsphere shears in Fig. 11 or Table III measured over ΔZ intervals from 100 to 1800 m are averaged, excluding those computed at the 400- and 200-m levels, the resulting average shear is the thin solid curve, $\overline{S}_J$, shown in Fig. 22. The thick solid curve S_n in Fig. 22 is the accepted 99 percentile build-up shear for a wind speed of 24 m s^{-1}, and is the shear envelope used to establish the synthetic wind profile (Curve Y) in Fig. 21.

A comparison between curves $\overline{S}_J$ and S_n shows very little difference relative to the shape or magnitude of the curves. It appears, therefore, that the currently accepted build-up shears for heights above 1 km could actually be used to compute synthetic wind profiles starting at levels as low as 600 m, assuming the directional or non-directional steady state wind profiles were established down to the 600-m level.

However, the Jimsphere shears computed from the 400- and 200-m levels over ΔZ intervals of 100 m and 200 m were significantly larger than those above 600 m for the same ΔZ interval. The dashed curves S_{400} and S_{200} in Fig. 22 are plots of these Jimsphere shears from the 400- and 200-m levels, respectively.

It is clear that both curves, S_{400} and S_{200}, are significantly different from $\overline{S}_J$ and S_n in both magnitude and shape, indicating the existence of much larger shears in the surface boundary layer (approximately below 400 m).

Therefore, the resulting Jimsphere synthetic wind profiles (Fig. 21), starting at the 400- and 200-m levels, have a shape different from those above the 400-m level since the build-up shears are larger below 600 m for a given ΔZ interval. Design build-up shears used to compute the synthetic wind profiles below 600 m should take into account these larger shears as measured from the Jimsphere data in the surface boundary layer.

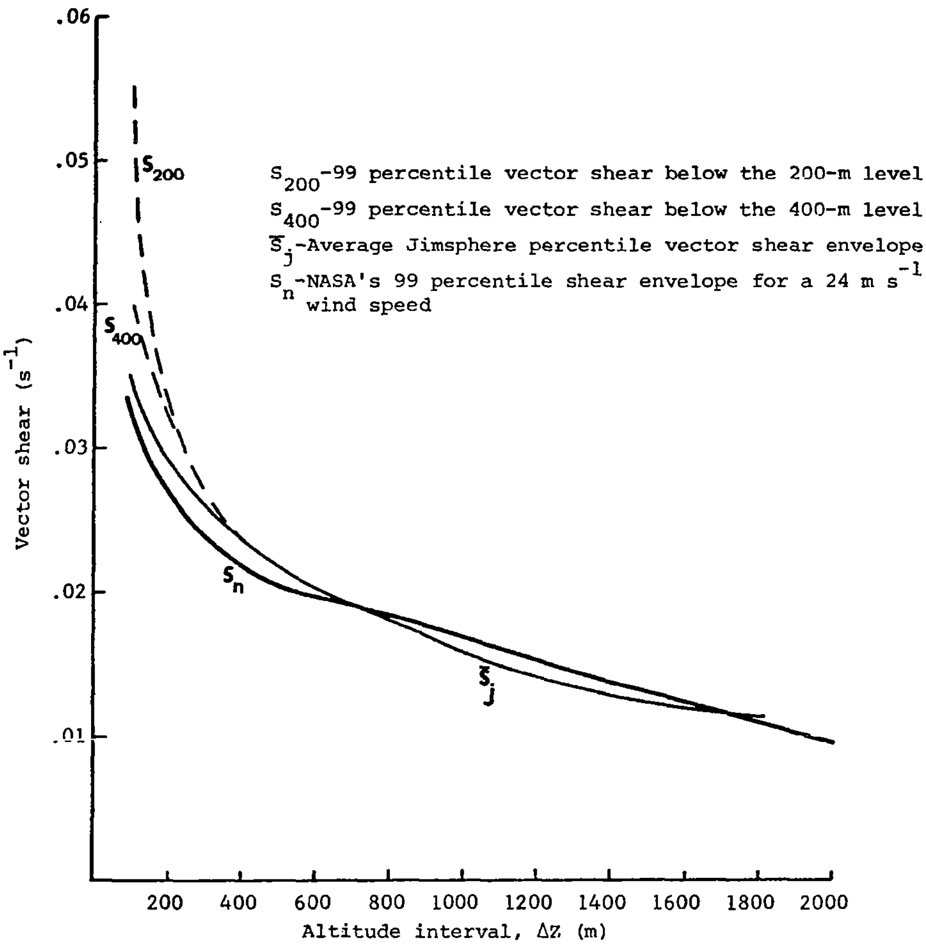


Fig. 22. Average Jimsphere vector wind shear envelopes (99 percentile) compared with established inflight 99 percentile envelope.

C. Wind direction change

Wind direction change as a function of height in the planetary boundary layer is difficult to specify in a meaningful way because it is a function of so many different parameters. For example, it is a function of stability, mean wind speed, the roughness of the surface near and upstream of the measurement point, the degree of averaging of the measured wind, and perhaps other variables. In addition, interference by the structure on which the wind instruments are located may be significant and a function of wind direction. The degree of interference usually is not known but may amount to several tens of degrees.

It would be unwise to attempt to specify wind direction change as a function of altitude for design purposes based upon the limited sample of data analyzed in this report. However, some general conclusions can be drawn which may be helpful. From the data presented in Paragraph 3D, (page 20) the wind direction change determined from tower data Set I when the wind speed was 5-7 m s^{-1} is much greater near the ground than those shown in tower data Set II when the wind speed was 10-20 m s^{-1}. In both instances, the magnitude of the wind direction change decreased rapidly with height and became essentially constant above approximately 200 m. The 99 percentile change varies from approximately 1.7 deg m^{-1} near the ground to approximately 0.3 deg m^{-1} between the bottom and top of the tower in data Set I, and is smaller in data Set II. These magnitudes are typical and support the information presented by Daniels (1973).

D. Gust factor

The gust factors derived for tower data Set I as a function of height and averaging time interval and presented in Paragraph 3E (page 26) are consistent with those presented by Daniels (1973). The average wind speed during the period of data Set I was approximately 6 m s^{-1}. The gust factors presented by Daniels for a comparable wind speed are slightly higher than those presented in this report which is to be expected because of the differences in the extent of data samples. While the data presented in this report is inadequate as a basis for establishing design gust factors, the results extend above the altitude presented by Daniels and show that the gust factor continues to decrease with altitude to a height of 444 m, and that the decrease at the higher altitudes is less than nearer the ground. A similar variation is presented in Table 5.2.29 by Daniels to a height of 152 m. The variation of gust factor with height and averaging interval shown in Fig. 16 could be used as a guideline for extending the gust factors presented by Daniels to a higher altitude.

E. Turbulence spectra

The spectra of turbulence presented in Paragraph 3F (page 26) confirms the general shape of the spectrum represented by Eq. 5.3, p. 5.35, in NASA TMX-64757 (Daniels, 1973). The decrease in energy with height above the reference level is also confirmed. The importance of the spectra presented in this report is that they indicate that the turbulent energy continues to decrease to a height of 444 m which is well above the altitude of 152 m specified in the NASA report. Preliminary indications are that Eq. 5.3 in NASA TMX-64757 could be used to extend the longitudinal and lateral spectra of turbulence to a height of perhaps as high as 500 m. However, before this can be done additional data should be analyzed and, therefore, no attempt is made here to alter the spectra currently used by NASA.

5. CONCLUSIONS AND COMMENTS

Two sets of tower data obtained from the NSSL tower facility located near Oklahoma City, and approximately 3700 Jimsphere profiles measured at Cape Kennedy, Florida, have been analyzed for the purpose of unifying the ground and inflight wind design criteria established by NASA. The ground wind criteria presented in NASA TMX-64757 extends to an altitude of 152 m while the inflight wind criteria begins at an altitude of 1 km. In the interval between 150 m and 1 km design criteria are not adequately specified because of the general lack of data in this altitude range.

Tower data analyzed in this report extends to a height of 444 m while the Jimsphere data overlaps both the tower data and the inflight data. Jimsphere data were analyzed in the altitude range between 100 m and 2 km and used as a basis for establishing steady state wind profiles and shears over intervals ranging from 100 m to 1800 m. The results of the analysis of the Jimsphere data make the most significant contribution to the problem of unifying the ground and inflight criteria because of the sample size and the confidence that can be placed in the results. These data are believed to be adequate for specifying the steady state wind profile in the region between 152 m and 1 km as well as the shear and wind speed change envelopes used in the construction of synthetic profiles associated with this altitude range. In addition, these data are believed adequate for establishing with reasonable accuracy the envelopes of component wind speeds. This has been done and the results are presented in this report.

Because of the small sample size of the tower data the results of the analysis of these data serve primarily to substantiate the ground wind criteria already established, and to provide general guidelines for the extension of the established criteria to a height of approximately 500 m.

REFERENCES

Carter, John K., 1970: The Meteorologically Instrumented WKY-TV Tower Facility, ERLTM-NSSL 50.

Conte, S.D., and Carl de Boor, Editors, 1965: _Elementary Numerical Analysis: An Algorithmic Approach_, McGraw Hill Book Company, New York.

Daniels, Glenn E., Editor, 1973: Terrestrial Environment (Climatic) Criteria Guidelines for Use in Aerospace Vehicle Development, 1973 Revision, NASA TMX-64757, National Aeronautics and Space Administration, George C. Marshall Space Flight Center, Alabama.

Maas, Stephen J., and James R. Scoggins, 1976: Structure of Atmospheric Turbulence in the Friction Layer Below 500 Meters, NASA CR-2650, National Aeronautics and Space Administration, Washington, D.C.

Scoggins, James R., 1966: Ground wind measurements and anemometer response, Paper presented at the Meeting on Ground Wind Load Problems in Relation to Launch Vehicles, NASA-Langley Research Center, Langley Station, Hampton, Virginia.

NASA-Langley, 1977